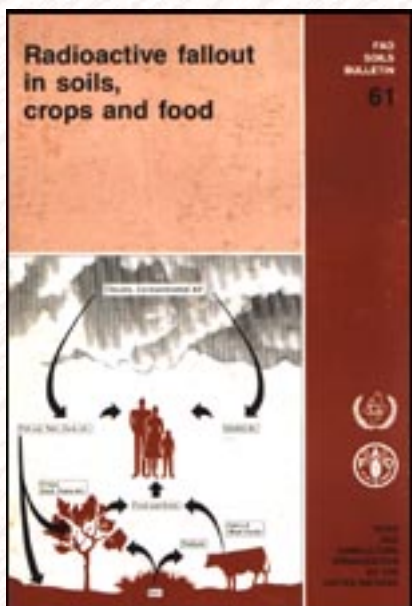




Radioactive fallout in soils, crops and food

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FAO SOILS BULLETIN 61

A background review

prepared by

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Notwithstanding its tragic human consequences the Chernobyl nuclear power plant accident in the USSR in April 1986 provided a timely reminder of the need for constant vigilance and preparedness. Above all, it demonstrated the importance of communication and cooperation at UN Agency level, and how the release of radioactive substances into the environment can rapidly achieve international and even global significance. The problems were especially significant in relation to agriculture, contingent food supplies, to their dependent communities and, therefore, in relation to FAO's interests and responsibilities.

The original FAO Atomic Energy Branch in Rome represented FAO's concern with the problems of radioactive contamination since the effective start of the "atomic energy era" in the first post - 1945 decade. This led to the now classical publications in the FAO Atomic Energy Series (see refs. 1 - 5). Responsibilities of the Branch were later transferred to the Joint FAO/IAEA Division in Vienna on the latter's creation in 1964 by a formal agreement between the two organizations.

Protection against the effects of radioactive fallout and contamination has, understandably, been a worrying subject for the layperson since the first atomic bombs of 1945. However, a proliferation of terms, definitions, the introduction of a new set of units of radioactivity and radiation levels, and a bewildering series of publications by the very many national and international organizations concerned have also complicated the subject.

Part 1) of this review is designed to provide an up-dated background to the subject in relation to FAO's interests and responsibilities in scientifically accurate but non-technical language.

Part 2) of this review is concerned more specifically with the problems of radioactive fallout over pasture and cultivated soils. Moreover, it is mainly concerned with problems of international significance under peacetime conditions and which are likely only to arise as a result of a major nuclear reactor accident or, possibly, some unintended nuclear explosion. However, relatively local problems of soil contamination could arise (and have done so) as a result of other kinds of accident. For example, by the failure of a land-based waste containment, or as a result of a crash by a military aircraft or space vehicle carrying radioactive material. (See sections 1.3.2 and 2.7.6).

References (see Section 5) are cited in the text for those seeking more technical detail or information. Mainly references to publications in English are cited but most UN publications will be available in the official languages of the Agency concerned.

The writer acknowledges FAO and IAEA colleagues too numerous to mention by name, for help and advice. Additionally, Prof. Karl Buchtela of Vienna, Dr. M.C. Thorne, former Secretary, I.C.R.P., Hr. Donald Doo, Manager of the Trawsfynydd Nuclear Power Station, North Wales, and the Martin Bunford

and Elwyn Evans families who sheep-farm in the hills of North Wales. Further information was generously supplied by Professor Elfyn Hughes (formerly Director, Nature Conservancy for Wales), Professor Mansel Davies (formerly Professor of Chemistry, University of Wales), and by Dr. Martin Frissel (Head of the Laboratory of Radiation Research, R.I.V.M., Netherlands). Abundant help notwithstanding, any shortcomings in this review remain the writer's responsibility absolutely.

EDITORIAL NOTE

In preparing this material for the press, staff of the Food and Agriculture Organization of the United Nations and the International Atomic Energy Agency have mounted and paginated the original manuscripts and given some attention to presentation.

Possible viewpoints implied in this study are those of the author and not necessarily those of the International Organizations or National Authorities mentioned. It is also stressed that needs and activities identified for possible implementation at international level may require modification on the basis of continuing post-'Chernobyl' experience and should, in any event, be subject to appropriate cost-benefit appraisal as indicated in the text.

The mention of specific companies or of their products or brand names does not imply any endorsement or recommendation on the part of the FAO or the IAEA.

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1. Behaviour and significance of radioactive substances released into agricultural, forestry and fisheries ecosystems

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1.1.1 Natural levels

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1.1.1 Natural levels

Radioactive substances are natural components of the entire biosphere, and some are constantly formed de nova in the atmosphere as a result of cosmic radiation (6) from outer space (especially carbon-14 and tritium or hydrogen-3).

Since all life on this planet has evolved and, evidently, flourishes in this radioactive environment it is useful to quantify these natural levels of radioactivity. This not only indicates "natural background levels", which must be known before trying to detect and measure anthropogenic increases, but it also indicates radiation levels which must surely be regarded as "acceptable". Indeed, like the air one breathes, there is no known alternative to acceptance on this planet.

Before the testing of nuclear weapons in the atmosphere, the latter contained radioactive carbon-14 (as carbon dioxide) equivalent to approx. 0,25 Bq g⁻¹ carbon. With the testing of nuclear weapons in the

atmosphere in the '60s the level reached a peak of approx. 0.45 Bq g^{-1} carbon but it later declined (7; 8; for units and terminology see Section 4).

Typical soils have been indicated to contain approx. $3 \times 10^5 \text{ Bq m}^{-2}$ of the natural radioactive isotope potassium-40 to a "rooting" depth of 20 cm (2). Seawater contains approx. 10 Bq l^{-1} of potassium-40 (2, 9). Food, feed, fruit and vegetables have been reported to contain approx. $50 - 150 \text{ Bq kg}^{-1}$ which is in line with the known potassium-40 content of natural potassium of 30 Bq g^{-1} (see also Section 2.3).

Rocks (and soils) and, therefore, derived building materials can contain certain natural "primordial" (as distinct from "cosmogenic") radionuclides of uranium, thorium, and actinium which show complex radioactive decay patterns with the formation of radioactive "daughters" such as radium-226 and the chemically-inert but radioactive gas radon-222. Levels up to approx. 10^4 Bq m^{-2} of radium in soils (to rooting depth) have been reported (2). Levels of natural radium-226 in food and water have been indicated in the following ranges (5):

Cereals	0.3 - 5	Bq kg ⁻¹
Fruits and vegetables	0.04 - 0.9	"
Milk	0.04 - 11	"
Groundwater	0.04 - 0.4	"
Surface water	less than 0.04	"

Levels, distribution patterns and anthropogenic changes in the environment are reviewed elsewhere (6), briefly discussed below, and in more detail in Part 2 of this review.

1.1.2 Manmade (anthropogenic) sources

Since 1945 there has been a large increase in the production of artificial radionuclides, originally with electrical sub-atomic particle accelerators (e.g., the cyclotron), with small radium-beryllium neutron sources, but, above all as a result of uranium fission and by neutron irradiation by the core of research or power-plant nuclear reactors.

In the context of accidental releases there is no doubt that the fuel elements of a stationary or mobile (ship or submarine) nuclear reactor represent the greatest potential source of unintended contamination of the environment. There is, additionally, the possibility of an accidental release of fissile material and fission products as a result of an accident involving nuclear weaponry, which is outside the scope of this appraisal, as is the possible release of radioactive substances as a result of war or terrorism. These considerations, however, do illustrate the urgency and importance of extending and implementing fully the "Non-Proliferation Treaty (NPT)" in which IAEA plays a central role (10).

The range and quantities of radionuclides which accumulate in the operational reactor core, or in structural or circulating media (e.g., cooling water) as a result of incidental neutron irradiation are well known. The fission products consist largely of elements of mass numbers lying in the range 80 - 160. Neutron activation products are those elements capable of effective "neutron capture" and which are temporarily or permanently resident in the reactor's containment structure, plumbing, circulating media, etc. These activation products include carbon-14 (from nitrogenous impurities in carbon dioxide-cooled reactors), manganese-56, cobalt-60, zinc-65 and the "transuranium" elements such as the plutonium isotopes-238 to 242 (2; 6; 11, 12) which are present within the reactor fuel.

While fission and radioactive products are produced at a constant rate under constant operational conditions some radioactive products reach a "steady-state" level. This level is reached when the rate of their radioactive decay balances their rate of production. Long half-life radionuclides, however, tend to accumulate continuously with the operational life of the reactor fuel elements. For these reasons the radiochemical composition of the reactor eve changes with time, as well therefore, as the range and levels of radionuclides to be expected in a post-accident release or fallout event.

The radionuclides most likely to appear in the environment as a result of an accidental or explosive release from a nuclear reactor are listed in Table I. The radionuclides of high potential significance to agriculture, food, feed, forestry and fisheries are marked. The selection takes into account earlier studies (2; 5; 11; 12; 13; 46) and some of the many ongoing ones following "Chernobyl" (14 - 18).

1.1.3 Radioactive wastes and discharges

Attention has been drawn to accumulation and production of radionuclides in reactors and their distribution for various uses. This implies local additions to the natural radiation levels of the human environment and releases of some radioactive wastes or by-products into the environment. However, because of their potential biological significance (see Section 2.4.1), the processing and transport of nuclear fuels and wastes, and the distribution of radioisotopes for use in medicine, research, and industry have probably been studied, and better controlled than any other kind of potential physical or chemical threat to human health. Likewise, a great deal of attention has in most cases been given to the siting of nuclear reactors, safety measures, and to the methods and routes for the transport, storage and disposal of radioactive wastes (23-30; 31; 32; 214).

Of importance when considering wastes is some understanding of the "nuclear fuel cycle" and the logistics for radioactive materials from the initial uranium ore mining operations, enrichment, fuel assembly, removal of spent fuel, reprocessing, etc. Descriptions of the "nuclear fuel cycle" in relatively non-technical language are available (29; 33; 34).

Table I

Radionuclides that may be released in a nuclear accident and with potential significance for agriculture, forestry and fisheries following a nuclear reactor accident

Radionuclide	Radioactive half-life	Emitted radiation	Degree of importance to agriculture	Remarks	
Barium-140	13 days	$\beta + \gamma$		FP	
Carbon-14	5,568 years	β	+	AP	
Cerium-144	284 days	$\beta + \gamma$		FP	
Cesium-134	2 years	$\beta + \gamma$	++	FP	
Cesium-137	30 years	$\beta + \gamma$	+++	FP	
Chromium-51	28 days	$\gamma + \text{X-rays}$		AP	
Cobalt-60	5.2 years	$\beta + \gamma$		AP	
Iodine-131	8.1 days	$\beta + \gamma$	+++	FP	Importance to Agriculture, etc. would decline within weeks of a release (see foot-notes).
Iron-55	2.6 years	X-rays		AP	
Iron-59	45 days	$\beta + \gamma$		AP	
Krypton-85	10.8 years	$\beta + \text{weak } \gamma$		FP	
Molybdenum-99	66 hours	$\beta + \gamma$		AP	
Neptunium-239	2.35 days	$\beta + \gamma$		AP	
Plutonium-238 etc.	24,000 years	γ	+	AP	
Ruthenium-103	39.5 days	$\beta + \gamma$	+	FP	
Ruthenium-106	368 days	$\beta + \gamma$	++	FP	
Silver-111	7.5	$\beta + \gamma$		FP	
Silver-110 m	270 days	γ		AP	
Strontium-89	52 days	$\beta + \text{weak } \gamma$	+	FP	
Strontium-90	28 years	β	+++	FP	
Tantalum-182	115 days	$\beta + \gamma$		AP	
Tellurium-132	78 hours	$\beta + \gamma + \text{X rays}$		FP	
Tritium	12.5 years	β		AP	

Zinc-65	245 days	$\beta + \gamma$		AP	
Zirconium-93	1.5 years	$\beta + \gamma$		FP	
Zirconium-95	65 days	$\beta + \gamma$		FP	
Xenon-133	5.3 days	$\beta + \gamma$		FP	

- FP denotes Fission products. AP denotes Activation products.
- "Daughter" isotopes of fission products, etc. not included.
- ^{239}Np and ^{238}Pu are Transuranium activation products or 'actinides'.
- The radioactive half-life (T_R) indicates the time needed for the level of radioactivity to decrease by one half as a result of radioactive decay alone (e.g., in a sealed sample of soil or water).
- The radioactivity of any radionuclide by decay alone is reduced to less than 0.1 % after ten half-lives. The reduction will be less than 10 % in 24 hr. for any radionuclide with a radioactive half-life of one week or more.
- The effective half-lives (T_E) of many critical radionuclides in livestock, as in man, may be very much less than the radioactive half-life as implied by the equation below. Thus, in the cow the effective half-life of ^{137}Cs is of the order of 20 days, and 2 - 3 days in the goat (see ref. 5; p. 107). It follows, for example, that if a cow grazes on ^{137}Cs -contaminated pasture for a limited period (e.g., for a month when the ^{137}Cs may have had time to move into the soil where it becomes relatively unavailable to the roots of growing crops or grass) the ^{137}Cs will tend to leave the cow on the basis of the effective half-life of 20 days. Therefore say, 3 months (approx. 4.5 effective half-lives) the level of ^{137}Cs in the meat or milk would be down to approx. 6 % of its initial peak value and down to less than 0.5 % after 6 months. However, if the cow continue to be exposed to ^{137}Cs contaminated pasture or contaminated stored feed the ^{137}Cs level will tend to reach a "steady-state level". when the rate of intake will be balanced by the effective rate of elimination.

$$T_E = T_R * T_B / (T_R + T_B)$$

where T_B is the biological half-life (see ref. 19, pp. 33-34).

1.1.4 Comparative radiation exposures under normal conditions

The protection of human health is, clearly, the main purpose of radiological protection. Adverse effects of ionizing radiation must be due to radiation absorbed from an external (i.e., to the body) source such as environmental radionuclides, an X-ray machine, or from an internal radionuclide absorbed through the

skin, inspired by the lungs, received in food and drink, or deliberately inserted for medical purposes (e.g., for the treatment of a malignant growth).

All human beings, either individually or collectively, are now exposed to ionizing radiation from anthropogenic sources as, indeed, they are also exposed to environmental chemicals: Dusts from mining, construction, demolition, the chemicals used in agriculture, for food preservation, emissions from motorized transport, fossil-carbon based heating, industrial effluents, etc. (35; 36; 37).

The significant question here is: What proportions of the total average population dose of radiation are respectively due to natural sources and the various anthropogenic ones ? This question has been studied and answered quantitatively, notably by UNSCEAR (13; 38) and several excellent publications in non-technical language are available (39; 40). The results are briefly illustrated in Table II.

TABLE II

Approximate relative contributions to the average annual effective dose equivalent from all sources.

Total exposure is equivalent to approx. 2.5 mSv yr⁻¹.

Source	% Total dose
Natural terrestrial internal sources (⁴⁰ K + ¹⁴ C + ²²² Rn, etc.)	54
Natural cosmic rays and external sources (Ground, building structures, ²²² Rn, etc.)	25
Artificial sources (Medical applications, X-rays, etc.)	19
Fallout from nuclear weapons testing	1
Air travel, TV sets, luminous paint, etc.	0,5
Nuclear power industry	0,2
	~ 100

An interesting result of more recent studies of exposure to natural radiation is the variation according to location, social habits (e.g., frequent flying), and that poorly ventilated spaces may accumulate significant increases in radon gas (²²²Rn) from ground and building materials (38). Clearly, individual exposure to man-made sources will also depend on behaviour, health, occupation, and proximity to routine and accidental releases and this may involve large individual variations.

An important factor in exposure after a nuclear accident would be through contaminated food and drink - even at great distances from the accident site and across international boundaries. Therefore, monitoring

the agricultural, forestry, and fisheries environment and restriction of the movement and export of possibly contaminated products, whether food, feed, components of drink, fibre products such as cotton and paper, will be important. This, in turn, can affect (as did the Chernobyl accident) the land, practices, and welfare of the dependent communities. These important problems will be discussed further (see Sections 1.4.2 and 1.4.9).

1.1.5 Accident sites and accident potential

This appraisal is concerned only with accidents under peacetime conditions of potential significance to agriculture, forestry and fisheries and to their dependent communities.

The relatively small quantities of radioactive substances involved, and generally strict controls on account of occupational hazards, suggest that accidents from industrial, medical and scientific research applications could only be of local significance, and unlikely to affect agriculture. There could be localized accidents affecting inland fisheries but these would not likely be on a scale which could not readily be contained.

The available information and experience to date including that of "Chernobyl" indicate that accidents of any potential significance to agriculture, etc., in order of importance would be:

- (a) Land-based nuclear power reactors
- (b) Mobile marine nuclear power reactors and air or space-vehicles carrying nuclear facilities
- (c) Reactors used for research, teaching, and radioisotope production
- (d) Fuel processing plants, waste discharges, etc. (especially into aquatic or marine ecosystems)
- (e) Mining, storage and transport of radioactive materials as part of the nuclear fuel cycle (excluding (d))
- (f) Nuclear-medical, industrial irradiation, and research facilities.

Clearly, the significance of any accident for agriculture, etc. will depend upon location, nature and magnitude of the release, and upon subsequent weather conditions. This highlights a need for a global map pinpointing the sites of all reactors and nuclear installations also showing the proximity of vulnerable agricultural, forestry and fisheries areas within, say, a 150 km radius of each site. Such a need in connexion with possible accidents of relatively local significance had been earlier identified (193, p. 51). Much of the necessary information and data for such a global map are already available (56; 83; 84; 85). Such maps would also be useful to 'non-nuclear' states which could, nevertheless, become exposed to radioactive fallout from a remote trans-boundary source as a result of weather-dependent atmospheric transport and deposition.

The location of nuclear powered ships or submarines could not be indicated by a static map and stresses the vital importance of early notification. A major step forward has been achieved since "Chernobyl" by the recent international Agreement on "Early Notification" in Vienna (41; 42; 43).

An important difference between a land and marine accident is that most of a radioactive release into the sea or into an inland water body would not lend itself to independent detection at a distance by the monitoring networks already established in many countries. On the other hand, the radioactivity would be largely contained, and move relatively slowly. This would delay and, probably prevent any significant contamination affecting agriculture, etc. (71; 210; see also Section 1.2).

1.2 Radioecology, behaviour, significance, models

1.2.1 Significance

1.2.2 Radioecology

1.2.3 Models

1.2.4 Anticipatory- and countermeasures

1.2.1 Significance

Given an accidental release, at least three questions arise: What is the behaviour of the radionuclides within the ecosystem ? What is their significance to human and environmental health ? What can be done about it ?

While its radioactivity enables a radionuclide to be detected, measured, and "traced" or followed within the ecosystem its chemical behaviour will be effectively identical with that of the normal non-radioactive element, or at least similar to the closely-related chemical elements naturally present. Thus, radioactive iodine - 131 behaves as the normal element iodine. Radioactive cesium - 137 behaves approximately like potassium. There are some minor "isotope effects", for example those due to transmutations on radioactive decay (see Section 1.5.2): Except for tritium, the small difference in mass number between the radioactive and stable nuclide can only very slightly affect the speed of chemical and enzymic reactions (47). However, such very small "isotope effects" are of no significance here. In short, while health effects are entirely due to radioactive decay and the emitted radiation, the ecological behaviour of the radionuclide will be entirely due to its chemistry (or biochemistry within a living organism).

As in the context of human health, radionuclides such as tritium and carbon-14, could become incorporated into the DNA structure of living organisms and, theoretically at least, have genetic or somatic effects on animals or plants of the ecosystem (48, 49). However, these radionuclides and their possible transmutation effects would not be significant in the context of effects on agriculture, etc. following an accident.

The chemical weights of fallout fission products and actinides will be so small as to be of no significance

in the context of chemical toxicology (or ecotoxicology). This has important implications when considering decontamination problems (see Section 1.2.4). However, because of the relatively high weights produced in the reactor core (34), its potential as a fuel in future "fast-breeder" reactors (33; 50) and its high radiotoxicity (51), plutonium-239 could, conceivably, be an exception in a future serious accident (see also Section 2.4.2). On the other hand it does not appear to be transferred rapidly through the food chain to man (52; 53).

The radiation of a contaminated ecosystem, at sufficiently high levels, can be directly injurious to microscopic life, plants and animals. Many studies have been made of these effects, e.g., on the biota of aquatic ecosystems (21). "Fish eggs have been considered one of the most sensitive components of marine biota" (see Nishiaki, et al. in the second part of ref. 21, pp. 195 - 209). These observations were made with aquatic ecosystems deliberately contaminated with radionuclides in the range of approx. 40,000 400,000 Bq l⁻¹. "No positive correlation between mortality and hatching rate of the eggs (Rainbow trout) and the radiation doses received" was observed. The doses ranged up to 0,07 Gy for cesium - 137 and up to 0,37 Gy for ruthenium 106 in a 30-day period of the experiment.

All these studies (see especially refs. 77; 183; 213) indicate that radiation levels so high in a contaminated ecosystem as to affect significantly any or all levels of wildlife, crops, livestock etc. would represent such a relatively serious threat to human health that direct effects on wildlife would have to be ignored in emergencies (54; 55). See also Section 2.4.2 for a more detailed discussion of these aspects.

1.2.2 Radioecology

Radioecology is the study of the behaviour of radionuclides in the entire biosphere, or in some particular ecosystem which could be a small experimental fish-tank, green house, or a 10000--hectare artificial ecosystem such as large hill sheep farm or cereal growing area. Radionuclides may be deliberately added for such studies or may have been the result of fall-out from the testing of nuclear weapons in the atmosphere or the result of a nuclear accident. The steady expansion of the nuclear power industry (56) has sustained an ever growing body of radioecological research and publication (refs. 1; 2; 3-5; 18; 20; 21; 22; 46; 53; 57; 58-62; 63; 64; 65; 66-75; 76; 77). Any detailed discussion of these wide-ranging studies is beyond the scope, or needs, of this appraisal. Instead, some of the significant findings will be indicated briefly.

The principal pathways and sources of internal or external irradiation following an accidental release are illustrated diagrammatically in Figs 1, 2 and 3 which are self-explanatory. Figs 1 and 2 illustrate the role of agriculture and fisheries in the transfer of radioactive contaminants of agriculture, etc. to man. Fig. 3 illustrates the special problem of external radiation for the farming community who spend a great proportion of time working in the open. They may also be especially exposed to external irradiation from harvested and stored products, such as hay (16). The possible transfer of external radiation sources to urban communities in the form of non-food products (e.g. wool, cotton, pulp for paper and news print, timber etc.) is not illustrated. Likewise, 'the generally minor' pathway (124, p. 44; see Section 2.2.2 (d)) of radionuclide transfer by atmospheric re-suspension is not shown in Fig. 1.

Fig.1 Principal pathways by which radioactive contaminants reach man from the air.

Fig.2 Principal pathways by which radioactive contaminants reach man from water.

Fig.3 External irradiation on farm from outside building structures and from barn-stored hay harvested after fall-out.

There is some evidence that fallout radionuclides over pine forests tend to be intercepted by the foliage (14) which will become ground "litter" and not, therefore, enter timber or pulp. Nevertheless, this potential problem may justify investigation.

Despite the range of potentially significant radionuclides (see Table I), in the experience of fall out studies and accidental releases only a few radionuclides have assumed major significance. These are strontium - 89, strontium - 90 (long term), ruthenium - 106, iodine - 131 (short-term), cesium - 134, cesium - 137 (long-term), and the plutonium isotopes, as largely anticipated three decades ago (53, p. 61; see also Table I and footnote).

The significance of iodine - 131, is due to its rapid transfer to milk and its accumulation in the thyroid gland. On the other hand, its relatively short radioactive half-life preempts the need for agricultural countermeasures beyond some 8 weeks after a single fall out episode.

Freshly deposited cesium - 137 (or, of course, cesium - 134) undergoes relatively rapid transfer from pasture into livestock, meat and milk. May harvested after a fall out episode and later used as feed can result in a delayed or new rise in the cesium - 137 levels of the resulting meat. Cesium 137 tends to become widely distributed in human muscle at the end of the food chain. Strontium - 90 behaves like calcium and is a bone seeker in man. Fallout over mature fruit or vegetable crops ready for harvest represents the highest probability of dietary intake in the absence of suitable intervention (see Section 3). Movement of deposited cesium - 137 and strontium - 90 down the soil profile under conditions of natural precipitation or irrigation tends to be very slow - a mere centimetre or so within months. Both radionuclides can be taken up through the roots of later crops but the availability of soil cesium - 137 is far less (about 1/10) than that of strontium - 90 (see also Sections 2.5 and 2.7). Both radionuclides can appear in harvested cereals after fall out over agriculture land. Milling and "high extraction" reduce their levels in bread.

Only very small fractions of the plutonium isotopes in soil tend to be taken up by crops (dry weight concentrations in the crop less than 1 % of those in the soil).

The extremely low chemical concentrations of fallout radionuclides do not favour direct translocation into the plant from foliar deposits at least not in the very early phase. However, while cesium - 137 in soil is taken up by crops less readily than strontium - 90, the reverse situation applies to their direct absorption from foliar deposits.

Precipitation is a major factor in the transfer of atmospheric borne radionuclides to land and water surfaces. Radionuclides released, intentionally (as waste discharges) or accidentally, into marine or fresh water fisheries become confined relatively locally. However fish and especially aquatic micro-flora may "bioconcentrate" the radionuclides by factors of 1,000 or more especially in oligotrophic lakes. Fortunately, again because of their low chemical concentrations they tend to become strongly adsorbed on particulate suspensions and sediment accordingly (e.g., see ref. 210). This in turn, fortunately, has hindered transport in rivers across international boundaries (71).

1.2.3 Models

Many mathematical models and simple equations have been developed for quantifying the movement and behaviour of radionuclides released into the environment (78; 79). This provides for the very important task of quantifying the relationships between the levels of deposited radionuclides expected in different parts of the ecosystem, times involved, and the overall transfer in the food chain to man. Also in the study and control of routine radioactive discharges (24, 80). "Market basket" and dietary data are, clearly, of vital importance in these estimates, and in the final estimate of radiation dose-equivalent rates or of commitments as a result of diet (81; see also Section 2.5). Computer-based models have provided for the rapid storage, retrieval and handling of the ever-increasing range of radio-ecological data (e.g., 59, pp. 125 - 134; 77, Vol. I, pp. 13 14, Vol. IV, p. 75; 80; 178; 187; 188). For an indication of the units and terminology used, principles of radiation dose estimates, limiting parameters for occupational and public health protection under emergency conditions, see Sections 2.4.3; 2.5.3; 3.1 - 3.3 and 4 (also refs. 40; 44; 81; 182; 205; 211).

In emergencies following accidental releases, models are increasingly being used for predicting likely pathways and, therefore, as guides to monitoring and sampling. They have also provided useful integrated descriptive scenarios in retrospect, e.g., after "Chernobyl" (18). However, because of the immense complexity and variability in any natural or agricultural ecosystem, the vagaries of weather, precipitation, and the unknown factors of any nuclear accident in the very early stages it is obvious that there is no substitute for constant vigilance and emergency onsite monitoring of "critical pathways" (see below), especially of air and precipitation, for radionuclide levels and composition as well as external radiation levels and corresponding dose equivalent rates. It must be on this basis that emergency intervention and countermeasures for agriculture, forestry and fisheries are implemented for the protection of public health.

There are, of course, infinite possibilities for sampling and monitoring for radionuclides appearing within the ecosystem and its complexity of foodwebs following accidental or routine releases into an aquatic system or as fallout over agricultural land. The "critical pathway" approach (e.g., see ref. 22 and 64, pp. 573 - 582 based on radioecological studies identifies the most important radionuclides and their pathways leading to human exposure and, indeed, to exposure of the "critical organs". Thus, "Chernobyl" confirmed the importance of the early monitoring of precipitation, pasture, green vegetables near harvest time, and milk for iodine-131. Its measurement in irrigation water for use on later crops would have been of relatively low priority. In short, the "critical pathway." approach is important for optimizing the

deployment of vital monitoring resources, especially under emergency conditions.

The problems of radioactive fallout over agricultural, forestry, and fisheries ecosystems are very briefly compared below. Those of fallout over cropped soils in particular would represent a much larger scale of potential threat to public health following a major nuclear power plant accident and are dealt with in part 2. For authoritative and detailed comparative studies, references should be made to the comprehensive but pre-Chernobyl work of Coughtrey, Thorne and their colleagues (77), and to the classical work of Scott Russell and his colleagues (53).

The different impacts of the same radioactive fallout episode over soil and aquatic ecosystems have long been recognized (53, pp. 47-50). Firstly, relatively mature crops, tree fruits, etc. could soon lead to dietary intake after harvest, and carry relatively high levels of the deposited radionuclides (see Part 2). However, fallout over a water body must first undergo some vertical distribution, and will tend to be adsorbed on suspended or sedimenting particulates, microbiota, etc. (71; 210), and time will be needed to undergo movement through the aquatic foodchain before bioconcentration or direct absorption by edible fish. In any event, inland fisheries usually represent a minor contribution to the diet of populations generally (ref. 53, pp. 63-82). For these and other reasons, aquatic food chains were earlier considered to be a relatively "minor source" of human exposure to radioactive fallout (53, p. 49). For these same reasons, time could diminish or enhance the radiological significance of dietary fish (53, pp. 385-392) and, once again, underlines the importance of post-accident onsite monitoring (see above). However, as already mentioned radionuclides can undergo high bioconcentration under oligotrophic conditions (21, pp. 473-481) as confirmed by post-Chernobyl experience with certain inland fisheries in Sweden (82). This suggests that the problems of inland fisheries exposed to post-accident fallout will justify further study and monitoring in future despite earlier viewpoints (see also Part 2).

Radioactive fallout as "wet" or "dry" deposition over agriculture, forestry or fisheries is illustrated diagrammatically in Fig. 4 and summarized in the footnotes (see also part 2).

FIG.4. Diagrammatic illustration of 'wet' and 'dry' deposition of radionuclides over agriculture, forestry, and fisheries.

A - Closed forest, dense tree cover, high foliar interception, soil protection by bound litter, exposed wildlife

B - Fruit trees, relatively high foliar- low fruit-interception.

C - Crazed pasture, high livestock intake after 'spike' deposition.

D - Greenhouse, potted plants only exposed to 'dry' deposition through ventilation.

E - High interception by mature green vegetable cover, potentially rapid entry into food basket. Potential soil protective cover.

F - Bare fallow after harvest and ploughing, maximal exposure of soil to subsequent deposition. Rapid vertical dispersion down the soil profile to ploughing depth after prior deposition.

G - Delayed but high bioconcentration by fish in oligotrophic water bodies. effective removal of radionuclides by particulate adsorption and sedimentation but bottom feeders relatively more exposed.

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1.2.4 Anticipatory- and countermeasures

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The first and essential conditions for a successful programme of anticipatory- and counter-measures for minimising and reversing the effects on agriculture etc. are prompt notification of the accident and activation of the available networks for monitoring significant changes in radiation levels of potentially vulnerable agricultural, forestry, fisheries areas at a distance. The need for maps in this context has already been indicated (Section 1.1.5).

"Chernobyl" has already prompted, with exemplary support by the USSR a major step towards an effective international agreement on prompt notification (41; 42) of a nuclear accident.

The IAEA has traditionally played a leading role in the development and testing of sampling and monitoring methodology for radiation and radioactivity. These programmes (based on the IAEA Laboratory at Seibersdorf in Austria, and Monaco) are now being expanded with improved cooperation and coordination among other U.N. Agencies including FAO (86).

Post "Chernobyl" experience has suggested one possibility of improvement in anticipating and implementing preventative actions on animal farms. Post accident weather and precipitation events played a critical role in radioactive fallout episodes - especially at the greater distances from the accident site (e.g. in parts of Austria, North Wales, Sweden). The role of precipitation in this context is well recognised (e.g. see pp. 1,955 et seq of ref. 74). This suggests that if post-accident meteorological conditions indicate the possibility of precipitated fallout, dairy and possibly, other livestock (lambs) could be rounded up and transferred to temporary or standing shelter, (a practice common in Europe in cold winter latitudes anyway), and provided with stored feed and water. This would need a permanent infra-structure for:

- rapid weather warning communication to farmers within range;
- standing or easily erected temporary shelter or cover with permanently maintained emergency feed and water resources;
- local monitoring advice to obviate unnecessary disruptions, or to indicate a return to normal conditions.

The recent expansion of remote sensing for meteorological forecasting, and land-based rain-storm radar warning systems (e.g. as in U.K.) suggest a potential for their emergency mobilization on notification of an accident.

Post-accident countermeasures (193) in the context of food and agriculture include the following:

- Interception of harvest, product movement and trade when post-accident Derived Intervention Levels (DILs) so indicate (see Section 3).

- Decontamination, dilution, processing, or simple storage (to allow for effective radioactive decay) to the extent of reducing contamination to acceptable levels.
- Containment, isolation, or disposal or equivalent restrictions on land and water use, even permanently in the case of serious contamination, e.g., sufficiently near the accident site as, indeed, occurred near the Chernobyl site (14, 46).
- Reclamation or use-recovery of exposed soil and water resources - the problems of soil-crop exposure are addressed in more detail in Part 2.

It would be the third kind of countermeasure that would have the most serious impact upon the dependent communities since situations could arise which would leave families or communities with no alternative to changes in habitation or occupation. Temporary switching to useful farm maintenance tasks, fence repairs, etc. could also be constrained by external radiation levels. However, it is stressed that these extreme constraints are most unlikely to be more than temporary, local, and probably within kilometres of the accident site. The accident itself would have to be a very serious one in the environmental sense. But the possibility must be recognized. These considerations also underline the importance of some kind of insurance and compensation provision (see Section 1.4.9).

Many reports refer to the problems of decontamination. An important aspect of "effective" decontamination by dilution or mixing the contaminated product or its processed derivatives with unaffected products (e.g., milk, cereals, processed meats, fish) is to ensure uniformity of the mixture. This to obviate the possible problem of "hot-spots" persisting in the final mix which could finish up in the diet of just a few individuals.

In relation to dilution or mixing it must be recognized that this would only reduce the individual dose to the normally exposed population. If, however, dilution or mixing resulted in a wider or time-extended consumption of the contaminated food fraction the collective dose equivalent commitment in total man-sieverts (54; see also Section 4) would remain little changed except for the effects of radioactive decay with time.

Some recent reports on the problems of decontamination of freshly harvested vegetable or fruit crops also suggest the need for investigation. For example, while "washing" fresh vegetables and fruit was widely recommended in Europe after "Chernobyl" (87) some observations indicated very different levels of effectiveness. "Useless" (Professor Hohenemser, et al. in a proposal dated 1 July '86 for an International meeting to be sponsored by IIASA and communicated to FAO?; iodine-131 activity reduced by "approximately 30 % and cesium-137 to "approximately one third" (87); "careful washing practices removed only half the activity and only 10 % of cesium-137 activity" (Professor Buchtela, Vienna - personal communication). Likewise, direct plant absorption from experimental foliar deposits of cesium-137, at low concentrations to simulate fallout conditions, has been reported as low 1.2 - 3.4 % according to species (63). Both classical (2) and post-"Chernobyl" observations have indicated, however, that "a large part of direct cesium-137 deposited on the leaves of growing plants ... was taken up ... and a fraction

transported to fruits and grain" (88). Discarding the outer leaves or skin of freshly harvested vegetables and fruit will, of course, remove recent deposits (89). Likewise, discarding the bran and outer layers of cereal grains would be expected to reduce strontium-90 levels (2).

A problem highlighted by "Chernobyl" was the uptake of iodine-131 and cesium-137 from recent deposits on pasture. This has prompted current research on feeding exposed sheep with suitable suspensions to reduce intestinal absorption of cesium-137 (Dr. Chesters, Rowett Research Institute, U.K. - personal communication). Iodine administration would also be expected to reduce iodine-131 accumulation in livestock but this might not be justified on economic grounds - at least not before investigation. While iodine administration would be expected to reduce the fraction of total body iodine - 131 in livestock thyroid it might actually increase the fraction appearing in the milk of lactating mammals (77, Vol. 3, pp. 341 et seq.).

Countermeasures directly related to public health are not within the scope of this appraisal (see paragraph above) such as the administration of iodine to reduce thyroid uptake of iodine-131 by members of the public. Such countermeasures are authoritatively reviewed elsewhere (e.g., refs. 90; 91).

As mentioned earlier, radionuclides deposited on the soil move down the profile more slowly than many plant nutrients, especially nitrogen in the form of nitrates (92). This would be expected on the basis of their generally cationic nature and the extremely low chemical concentrations involved (see below). This implies greater availability for uptake by shallow rooted crops as well as for further spreading as a result of surface erosion. For these reasons, ploughing (to a depth of about 30 cm) is recognized as a useful and practicable countermeasure at farm level (2; 58; 90). Serious levels of contamination (e.g., because of proximity to the accident site) may dictate actual removal of the topsoil and dumping in a protected site as anticipated for the case of nuclear warfare (89) and as actually implemented around Chernobyl (14, 46).

Uptake of strontium-90 can be reduced by liming when soil pH and calcium levels do not contra-indicate (58). The addition of gypsum (calcium sulphate) has also been suggested for reducing strontium-90 uptake from saline or alkaline soils (2).

Contamination of marine and inland fisheries (ponds, lakes, rivers, etc.) by fallout is not considered a serious problem because of confinement, dilution, and sedimentation. However, within freshwater fisheries and lakes of low nutrient status cesium-137 levels were expected to reach levels of 1,000 Bq Kg⁻¹ or more in fish in parts of Europe following "Chernobyl" (88). This suggests the possibility of adding appropriate nutrients to small inland fisheries as a countermeasure.

The administration of suitable ion exchange resins (e.g., containing ferric ferrocyanide), alginates, etc. for decreasing gastro-intestinal uptake of ingested radionuclides is well recognized (93; 94; 91) and suggests potentially useful application to farm livestock in certain post-accident situations.

Notwithstanding the evidently variable effectiveness of simply washing freshly harvested products (see above), food processing 'beyond the farm gate' may also involve mixing, peeling, cereal extraction,

canning, drying, etc. etc. as described in many classical publications (e.g., 95; 96; 97). This, likewise, will affect the derivation and application of appropriate DIL's (see Section 3) and the relation to the level of radionuclide in the final plate of food or drink to the initial level after exposure under field conditions. Overall effects of food processing on the fractions remaining of "external contamination" of freshly harvested fruit and vegetables and those of "internal contamination" have been studied. Quantification of these effects as well as the effect of time itself will also dictate the DIL to be applied at some initial, intermediate, or final stage of food processing to allow for the corresponding changes in level of radioactive contaminant.

Some effects of processing on fruit and vegetables are briefly illustrated in Table III below (see also Section 3.3).

Some of the apparently differing implications of decontamination and weathering studies during the last three decades may have arisen because of two factors: The critical factor of time between deposition and attempted decontamination by experimental washing or by the effects of natural precipitation. Secondly, the extremely low chemical concentrations of fallout radionuclides which might not be simulated effectively in experimental studies. The chemical weights of the effectively "carrier-free" (i.e., as the isotopically pure radionuclide) fission products within a reactor core have been indicated (11). Likewise, the levels of radioactivities released in the Chernobyl accident (88). These considerations indicate that, in the case of cesium-137 for example, considerably less than 100 kg weight of the radionuclide was deposited over an area of not less than 10 million km². This implies an average surface deposit of less than 1 picogram per square centimetre, and a concentration less than .0001 parts per 10⁹ in the top 10 cm of soil. Classical adsorption and diffusion theory (166) indicates that the removal of surface contamination by simple washing would be difficult, especially after much delay after deposition. Moreover, some radionuclides such as iodine-131 might undergo "isotopic exchange" with trace iodine compounds likely to be present naturally in soils and plants. This means the fallout radionuclide would effectively become incorporated into chemical structures near the plant or soil surface.

TABLE III

Illustration of radionuclide levels of processed fruit and vegetables for consumption expressed as fractions of the levels of "internal" leaf or flesh before washing, peeling, canning, etc. (from ref. 81, pp. 68 & 70).

	Strontium-89/90	Cesium-134/137	
Spinach		0.36	0.12
Tomatoes		0.35	- - -
Peaches		~ 0	~0
Broccoli		0.28	0.11

However, for these same reasons, the addition of suitable carrier of non-radioactive cationic salts (e.g., of calcium, potassium, or even natural cesium) to the washing medium would be expected greatly to improve the effectiveness of sample decontamination (e.g. of freshly exposed and harvested vegetables) by rinsing, a long and well-recognized radiochemical laboratory practice. Research workers familiar with rinsing out glassware which has merely contained a solution of some "carrier-free" radioisotope will be fully aware of these problems!

The problems of the safe disposal of seriously contaminated soils, crops, or livestock must be the responsibility of the national or local authority and will, surely, need expert guidance (85; 98; 99).

To conclude this section: Despite the body of research and publication (e.g., 1-5; 16; 18; 21; 22; 52; 57-66; 77; 88;) there remains a need for clear and simple guidelines on preventative measures (i.e., in anticipation of possible future accidents), for an evaluation of existing countermeasures, and a suitable publication for use at the agricultural college, extension service or farm levels.

Finally, while existing guidelines have been, understandably, mainly concerned with public health (90; 100), the indirect effects of a possible accidental release upon agricultural, forestry and fisheries-dependent communities had been relatively neglected before "Chernobyl" (see Sections 1.4.2 and 2.8).

1.3 Chernobyl and other accidents

1.3.1 Chernobyl

1.3.2 Other accidents

1.3.3 The international situation in Europe after "Chernobyl"

1.3.1 Chernobyl

In the context of the nuclear industry, the accident at the Chernobyl nuclear power station on 26 April 1986 has, undoubtedly, been the most serious and one with consequences for agriculture, etc. on an international scale (see Section 2.7 for discussion in the agricultural context).

As a result of the prompt and exemplary gesture by the Soviet Government to communicate and to cooperate through the U.N. system with IAEA as the focal point, full and technically-detailed reports on the accident rapidly became available (14, 46; 148).

Sufficient here to mention that the accident involved an explosive emission of some 50 MCi (approx. 2×10^{18} Bq) of radioactive substances (excluding krypton - 85 and xenon - 133) equivalent to 3-4 % of the total radioactive content of the reactor core likely to have been present at the time. This, in turn, led to significant radioactive fallout episodes in many countries of Europe outside the USSR and to detectable fallout up to many thousands of kilometers distant within days - e.g., in the USA (101, see also Section 2.3.4).

Radiological protection measures involving constraints on agriculture, food products, etc. were imposed in many countries (88; 87). In the critical area around Chernobyl acute effects of radiation exposure were diagnosed in some 200 people with some 30 fatalities to the end of July, 1986. With regard to possible late stochastic effects (see note on terminology in Section 4) it was estimated that some 200 cases of late cancer fatalities might result. This would add less than 1 % to the expected cancer mortality of the affected population which will be expected in the normal course of events. Additionally, it was "conservatively" estimated that the "average" person of the 75 million living in the most exposed Western region of the USSR will have received a total dose equivalent commitment which, on the base of the then currently recognized ICRP risk factors, would result in an increase of less than 0.3 % in the cancer deaths expected to occur in the population during the next 70 years and corresponds to less than an increase of 0.1 % in the corresponding expected total mortality (46).

On the continental scale, Europe as a whole experienced the greatest impact on food and agriculture as distinct from direct effects or risks for human health. An assessment on the CEC's behalf of stochastic risks of late cancer as a result of Chernobyl in the EC countries has indicated a possible additional 1,000 cancer deaths over the next 50 years. It was pointed out that it can be expected that "30 million people in these European countries will die from cancer of one type or another" over the same period in any event (102). In the same connexion it might also be noted that on the basis of annual road accident statistics (103), at least 3 million people may expect to lose their lives with a further 60 million injuries within the EC countries over the same period.

A recent estimate has indicated a possible 39,000 cancer deaths worldwide as a consequence of 'Chernobyl' over the next 50 years. However, this figure will be lost in a "sea of 630 million cancer deaths" expected globally in the same period (104).

1.3.2 Other accidents

Notwithstanding the gravity of the Chernobyl accident it is important to view it in the context of all technology-based accidents (105).

There have been a number of minor nuclear accidents which, understandably, tend to attract media attention because of public sensitivity to any kind of "radiation threat" associated with nuclear war (see Section 2.7.6).

The more notable accidents include that of Windscale (U.K.) in 1957 which involved the release into the atmosphere of some 20kCi (10^{15} Bq) of iodine-131 and 13 kCi (5×10^{14} Bq) of other radionuclides. The releases were detected on the mainland of Europe. Emergency countermeasures dictated by this accident were temporary constraints on local dairy production and the withdrawal of milk supplies in an area of 500 square kilometers (5).

Another accident occurred at the Three-Mile Island reactor site in Pennsylvania (USA) in 1979 involving serious damage to the reactor core and plumbing. However, radioactive material was almost entirely

confined within the outer containment structures. Some 43 kCi (1.6×10^{15} Bq) of radioactive krypton-85 (a chemically inert gas) were deliberately vented later to facilitate safe operation around the damaged reactor (106, 107, 108).

Marine accidents of potential radiological and fisheries significance have occurred. The cargo ship "Mont-Louis", carrying 350 tons of uranium hexa-fluoride destined for enrichment in the USSR and later use in Western European nuclear power plants, sank in the North Sea in 1984. The "nuclear" nature of the cargo attracted a good deal of media attention although at no time was a nuclear release involved. All the uranium hexa-fluoride was recovered intact (109).

An accident occurred when a Soviet nuclear submarine sank in deep water in the North Atlantic on 6 October, 1986 following an obviously serious explosion or fire within the submarine. According to later reports the nuclear power unit was itself not involved and "there was no danger of a nuclear explosion or radioactive contamination of the environment" (110).

There have been many reports of minor accidental increases or discharges of radioactive wastes generated as part of the "nuclear fuel cycle". E.g., in processing plants such as Sellafield (formerly Windscale) in the U.K., where plutonium, and fission products are separated from "spent" reactor fuel elements. In early studies of discharges into the Irish Sea from the Sellafield plant, ruthenium-106 evidently comprised about half the radioactive discharge into the sea and was the "critical" radionuclide. Ruthenium-106 undergoes bioconcentration by the edible seaweed Porphyra umbilicus which is a dietary constituent ("laverbread") of local importance to coastal communities (37).

1.3.3 The international situation in Europe after "Chernobyl"

"Chernobyl" prompted a great deal of media attention, the usual proliferation of "instant experts", and an escalation of publications, and proposals for meetings and new programmes. Reference has been made to the prompt action of both the Government of the USSR and the IAEA in the global context (14; 46; 41; 86; 111-115; 116; 117, 43). This note briefly mentions responses of the WHO-ACE, the CEC on the basis of the EURATOM treaty, and COE.

The WHO-ACE convened a meeting of experts as early as 6 May 1986 to appraise the immediate problems across Europe (118). This prompted a useful meeting and report of the situation at Bilthoven 25 - 27 June 1986 (88). Meanwhile, WHO not only collected information on fallout levels, locations, and implied dose-equivalent commitments but made this information rapidly available to international and national authorities (87). A concise summary of the situation for Europe after the first two or three critical months is available (118). Maps have been prepared indicating the levels of cesium-137 and iodine-131 deposition.

Deposition of cesium-137 varied from effectively zero (e.g., Southern Spain) to more than $3,000 \text{ Bq m}^{-2}$ over large areas of Europe and exceeding $100,000 \text{ Bq m}^{-2}$ within hundreds of kilometers of the Chernobyl accident zone.

An important and significant (but not surprising) observation was "hot-spot" deposition associated with local rainfall. Likewise, deposition maxima for iodine-131 were indicated.

Models were especially useful in this exercise in rationalizing the distribution of fallout and displaying comparative and expected deposition as a function of weather conditions, air flow, etc. It was concluded that around the "periphery of Europe" the total dose-equivalent commitment as a result of the current year of exposure (due to all external and internal sources) would be some 100 μ Sv for adults (i.e., approx. 10 % above existing background level - see Table II) but up to 30 % above background levels for children (118).

The CEC likewise acted promptly. For example, on 6 May 1986 circulated and recommended member states to observe "maximum tolerances" for levels of radioactivity in milk, milk products, fruit and vegetables for home marketing and trade (119). As with the UN organizations the CEC was also consulted about a range of problems, e.g., by the CIPF on the effects on international trade as a result of the accumulation of radionuclides in post-fallout harvested straw and fodder (16).

Recent announcements (120; 84) drew attention to the vital commitment to nuclear power within the EC, and the need for observing common internationally agreed radiation protection standards. Under normal conditions these should be based on the ALARA - principle. This is, basically, the ICRP recommendation that "all exposure to ionizing radiations must be kept at a level that is as "low as reasonably achievable" (121).

A later communication (84) stressed the need for the harmonization of "limits on foodstuff contamination". A useful map indicating the locations of nuclear installations in the EC and in neighbouring countries illustrated the potential value of a related map in the context of FAO's responsibilities (see Section 1.1.5).

It is significant that "Chernobyl" has demonstrated that, despite the relatively sophisticated technical infrastructure of Europe for handling nuclear accidents, there still remain serious and urgent problems of international communication, cooperation, and harmonization. Within the CEC "Chernobyl" had prompted "very disquieting conclusions" in that respect (122).

Parliamentary hearings convened in Paris (8-9 January 1987) by the Council of Europe provided for brief technical reports on the nature and magnitude of the 'Chernobyl' impact upon European agriculture, and for discussions by representatives of the many national and international authorities present (123, pp. 137-193; 132).

Since 'Chernobyl' there has been a continuing stream of national and international meetings, symposia, reports, publications, media presentations, etc. However, their monitoring by the writer to the end of July 1988 has not indicated the need for significant changes in this review except to underline that considerable time may have to elapse, before a full and balanced appraisal will become possible. Similar caution is implied by the Secretariat of UNSCEAR (124) in their assessment of the long-term impact

(mainly upon public health in Europe) of the Chernobyl accident (likewise in relation to the behaviour of 'Chernobyl' fallout cesium-137 in affected hill sheep-farm areas continuing studies will be needed for longer than originally thought (125).

1.4. Some international implications

1.4.1 Joint FAD/IAEA programmes

1.4.2 Lessons for the future

1.4.3 Collection of information

1.4.4 Autonomous monitoring facilities

1.4.5 Laboratory activities

1.4.6 Training and education

1.4.7 Communication and cooperation

1.4.8 International insurance system

1.4.1 Joint FAD/IAEA programmes

Many of the problems reviewed here are of mandatory concern to FAO (126). On the basis of their Joint Division facilities, FAO and IAEA are in a unique position to address many which have emerged since April, 1986. This Division was created in 1964 by a formal agreement between the two organizations. "Technical fields of responsibility" of the new Joint Division included "Radiation protection in food and agriculture, without prejudice to the responsibilities of the then IAEA Division of "Health, Safety and Waste Disposal" (127). The IAEA Division was traditionally concerned with safety in the nuclear industry and with radioactive waste management.

As indicated in the explanatory notes, FAO's concern with radiation problems parallels the "atomic energy era" itself. This continued through the Joint FAD/IAEA Division with representation at IAEA and UNSCEAR meetings, organizations of international meetings and symposia on the comparative aspects of chemical and radioactive contaminants, specific research under contract, publication of "Joint FAD/IAEA Comparative Summaries of Information" on radioactive contaminants, etc. (1-5; 7; 26; 36; 37; 58; 59; 63; 64; 128).

The Director General of FAO's statement at the 12th Session of the World Food Council in Rome, 16 June 1986 (129), and the establishment of the FAO Inter-departmental Standing Committee on Radiation Effects, 19 June 1986 (130) reflect FAO's current concern with these problems.

1.4.2 Lessons for the future

In terms of the range of radionuclides released, their widespread dispersion, transport and behaviour in exposed ecosystems; all these were largely as would have been expected from previous studies. Scientifically, very little new has emerged so far. The local emergency measures taken in terms of fire-

fighting at the Chernobyl reactor site, containment of the damaged reactor, evacuation of the local community, and medical treatment of the casualties appeared to have been remarkably prompt, well organized, and effective.

The first lesson was, that in order to ensure full public health protection in affected countries across Europe, serious constraints were imposed upon agricultural activities, product and livestock movement, and trade. These with little or no warning, explanation, or indication of possible compensation, guidance about the future to the communities concerned.

The second lesson was an exposure of the need for an improvement in international communication, cooperation and coordination under the conditions of a nuclear emergency. The IAEA has taken some prompt action with the support of member states (2; 43).

The third lesson is the need for simplifying and harmonizing, internationally, the evidently superfluous and often confusing terminology, jargon, units, limits, intervention levels and, above all, scientifically sound guidelines. Guidelines for use at national or even local authority level for what is now, clearly, a potential problem of international or even global proportions. This would facilitate effective protective measures, international trade and understanding and, therefore, public acceptance of nuclear technology in what also appears to be in the public interest for the immediate decades ahead.

The "lessons" identified above have been based mainly on studies of reports (e.g., 111-132; 150; 157; 204; 212) issued during the first post -"Chernobyl" biennium.

1.4.3 Collection of information

Post-Chernobyl experience suggests that the most important needs in the context of this review are:

- (a) Feasibility study of early warning networks for possible fallout episodes over agriculture and fisheries (see Section 1.2.4).
- (b) Preparation of a global map showing the juxtapositions of nuclear installations and agricultural, forestry, and fishery areas, together, if feasible, of the products and destinations, e.g., fish for local consumption, cereals or meat for export (see Section 1.1.5).
- (c) Information on capacity for anticipatory or "preventative" measures to protect livestock, etc. should a fallout event materialize, e.g., by international questionnaire to Member States (see Section 1.2.4).

1.4.4 Autonomous monitoring facilities

Reference has been made to the importance of early notification and action taken by IAEA (41; 43). However, "Chernobyl" experience has also indicated a need for improved communication to farm level. This, in turn, suggests scope for wider independent facilities for local monitoring, especially within the

150-km range of nuclear installations. In trained hands, and with relatively simple portable equipment, it is not difficult to detect a significant rise in radioactivity level, e.g., in rainfall over pasture or crops. Such provision might also obviate unnecessary suspicion or alarm. In many countries the available expertise and simple monitoring facilities already exist and it should not be difficult to set up small highly mobile units to visit worried communities and to communicate in simple language (e.g., several agricultural nuclear research facilities have already been created in "less developed" countries).

1.4.5 Laboratory activities

In planning future laboratory activities (e.g., on simple vegetable decontamination by washing with suitable water solutions) or investigations it could be wasteful to ignore the range of data and information already available, as reviewed here and in Part 2.

There would otherwise be a danger of mistaking priorities or "reinventing the wheel". In this connexion improved cooperation and information exchange between the U.N. Agencies and other international bodies such as the CEC, COE, OECD-NEA, and IUR would be of value since these organizations have been especially concerned with the post-Chernobyl situation in Europe and where the effects upon agriculture have, undoubtedly, been greatest.

1.4.6 Training and education

It is one thing successfully to prepare a non-technical description of the nature and consequences for agriculture etc. of a major nuclear accident. It is another thing to communicate it to those who may need it at farm, extension service, or agricultural training levels.

The Joint FAD/IAEA Division has successfully organized training courses in many countries and established nuclear research and training centres, e.g., in Bangladesh, Brazil, India and Yugoslavia. These have been mainly concerned with stable, radioactive isotopes and irradiation applications for agricultural development (133).

The information here reviewed suggests a need for new training courses in post-accident fallout monitoring, countermeasures, etc. applicable in the context of agriculture, forestry, and fisheries. Such courses should also include monitoring procedures for fallout or accidental release episodes, and the radioecological background to the development and application of DIL's at farm or fisheries levels.

1.4.7 Communication and cooperation

"Chernobyl" has certainly demonstrated the urgent need for improved international communication and cooperation. The situation is complicated by the proliferation of national and international organizations concerned with applied nuclear science, safety, radiological protection and radioecology. This has led to duplication of effort, sometimes contradictory or confusing recommendations and, above all, an expanding universe of publications and reports already beyond the specialist's telescope (see also 1.4.5

above)!

1.4.8 International insurance system

A major international consequence of "Chernobyl" was economic loss and psychological stress as a result of constraints imposed by national authorities on agriculture in the interests of public health protection. These constraints involved land use, livestock movement and trade - especially in relation to milk, meat, and fresh vegetables (see also Section 2.1.2).

There is a need for an internationally agreed system of farm and fisheries insurance against such losses as earlier foreseen (26) when nuclear power was on a very much smaller scale than it is today. Many reports in the European media have illustrated disparities in various Government reactions to this problem after "Chernobyl". Such an insurance scheme would certainly obviate some of the stress problems affecting the agricultural and, possibly, fisheries communities in future. It would seem logical to set it up as an international scheme sustained by national subscriptions based on their relative scales of nuclear power production.

The number of significant accidents in this context has clearly been very small in the past (see Section 1.3.2). Allowing for the obvious difficulties of reliable forecast (117), the probability of significant accident in future would also appear to be low (45). These considerations suggest that the costs of sustaining such an insurance scheme per GW(e)-year would be relatively low. However, the benefits in terms of confidence and sense of security among agricultural and fisheries communities, especially those near nuclear installations, would surely be high.

1.5 Summary

The natural occurrence of radionuclides, and radiation exposure as a fact of life in the human environment, are indicated. Exposure to ionizing radiation from natural and man-made sources are compared (see also Part 2).

The behaviour and significance of radionuclides in ecosystems (radioecology) are briefly illustrated (see also Part 2).

Land-based nuclear power stations and nuclear-powered ships and submarine are identified as the mayor potential accident hazards to agriculture or fisheries under peacetime conditions.

"Chernobyl" has high-lighted several problems of concern to FAO and her member states. To ensure the protection of human health serious constraints were imposed by national authorities upon agricultural practices, harvest and movement of crops and livestock in many countries across Europe with adverse financial and psychological problems for the dependent communities concerned. These consequences had been largely unforeseen or prepared for.

There is scope for the development of more effective anticipatory, protective, and countermeasures for agriculture, etc. and for their dependent communities in the event of a possible mayor radioactive release in future. Likewise, for international guidelines for insurance and compensation. There is also scope for improved international harmonization of guidelines, terminology, and acceptability of post-accident food and feed moving internationally.

In connexion with the behaviour of radioactive fallout from 'Chernobyl' over agriculture, forestry, and fisheries further years of study and data collection may be needed before a full and balanced appraisal will become possible (see also Part 2).

Finally, "Chernobyl" has not affected the international priorities implied by the statement attributed to Soviet Academician Velikhov at a U.N. Conference in Vienna in 1979 - "people should worry about the bombs, not power stations" (134).

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2. Soil and crop contamination by radioactive fallout

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2.1. Agricultural and forestry soils as a vital global resource

2.1.1 Soil as a limited resource

2.1.2 Radioactive contaminants and Pollution

2.1.1 Soil as a limited resource

Escalating technology, virtual consumer saturation, and apparently abundant food supplies in the spreading, 'super-markets' of the industrialized nations tend to obscure the fact that food, unlike all other human acquisitions or products, is literally vital to human survival. Food, in turn, critically depends upon the soil and water resources of the finite human environment. Moreover, food supplies for the present world population can now only be sustained by the application of increasingly intensive agricultural practices to effectively diminishing soil and water resources per capita (135; 136).

2.1.2 Radioactive contaminants and Pollution

The serious nuclear accident at the Chernobyl power plant on 26 April 1986 in the U.S.S.R. demonstrated dramatically the vulnerability of agricultural resources to radioactive contamination from atmospheric fallout. This affected large areas across Europe up to thousands of miles from the accident

site. Except for people exposed to the radiation occupationally or on account of proximity to Chernobyl, public health was effectively protected. Within the Soviet Union prompt action by the authorities which involved a large scale evacuation had clearly greatly contained threats to human health (14; 46).

Across Europe as a whole, however, public health protection involved some serious constraints upon agricultural and farm practices, harvest, and food movement. These, in turn, created problems of finance, compensation, and psychological stress for many of the dependent communities. For example, an understandable fear among some exposed agricultural land owners that post-"Chernobyl" fallout would adversely affect the market value of their farm properties (212).

All soils of the world are radioactive as a result of cosmogenic and/or primordial radionuclides naturally present. These, respectively, include traces of radioactive carbon (carbon-14) and radioactive hydrogen ("hydrogen-3 or tritium) formed by the action of cosmic rays in the atmosphere and which reach the soil through soil-borne photosynthesis and water absorption, and the naturally radioactive elements of potassium (potassium-40), uranium, thorium and their 'daughters'. The latter are present in the geological precursors of many soils.

Since the effective start of the 'atomic energy era' with the construction of the first nuclear reactor in Chicago in 1942 there has been a series of additions to soil radiation levels as a result of human activities: From the testing of nuclear weapons, their military use in the final stage of 'World War-II', as a result of controlled releases as radioactive wastes from the peaceful uses of atomic energy, and as a result of nuclear accidents which include those of Windscale (U.K.), Three-Mile Island (U.S.A.), the crash of a U.S. military aircraft evidently carrying thermonuclear bombs containing plutonium (in Spain), and Chernobyl (U.S.S.R.). Fortunately, most of these additions to the levels of soil radionuclides have not involved levels of any public health significance.

In general, it is important to distinguish between the mere presence of a chemical 'contaminant' of soil (whether radioactive or not) and one which becomes a 'pollutant' as a result of location, concentration and adverse biological or toxic effects.

2.2. Soil in the nutrient cycle

[2.2.1 Composition and variability of soils](#)

[2.2.2 Agricultural and forestry ecosystems](#)

[2.2.3 Cycling of plant nutrients and fertilization](#)

2.2.1 Composition and variability of soils

Soils are the relatively thin film of heterogeneous particulate and fibrous matter which constitutes much of the land-atmosphere interface. They are a complex mixture of minerals, carbonaceous matter and water, in which live the vast range of soil micro- and macro-flora and fauna.

Composition, classification and distribution of soils have been authoritatively reviewed elsewhere (e.g., 137; 138; 139; 140). Certain features are especially relevant to the problems of radioactively contaminated soils, especially the great variability of the soil-based (as distinct from aquatic-based) ecosystem in terms of chemical composition and of physical structure, and of environmental and exposure factors.

Composition varies especially in organic matter (both humus and undecomposed plant residues), inorganic matter, pH, and the availability of plant-essential elements (N, P, S, Na, K, Mg, Ca, Cl, B, Co, Cu, Fe, Mn, Mo, and Zn); of elements taken up and which may have a plant-biofunctional role or an essential role for grazing animals or human food (Cr, Ni, Se, Si, V, Br, F, and I); and in contaminants (e.g., pesticide residues, radionuclides, etc.). Plant C, H, and O are, of course, derived by photosynthesis and from atmospheric and irrigation water. Physical structure also varies in terms of the soil profile, soil water capacity, porosity, ground water level, topography, etc.

Environmental factors vary in terms of climate and weather; floral cover and dependent fauna; agricultural and/or forestry practice. These, in turn, vary with time, e.g. mature crop ready for harvest, post harvest bare fallow, or tend to remain in a 'steady state' like dense permanent cover of the tropical rain forest, permanent pasture, etc. Location, especially in relation to potential nuclear accident sites and radioactive fallout areas, is perhaps, the critical variable here. Clearly, such variability will influence decisively the levels, behaviour and significance of radioactive contaminants reaching a particular soil-based ecosystem as well as the kind of countermeasures which may be needed.

2.2.2 Agricultural and forestry ecosystems

Of particular importance will be the degree of soil exposure at the time of radioactive fallout (in precipitation or as 'dry deposition'). Soils under bare fallow would obviously be most exposed while those under dense vegetation would be least. For these and other reasons it would be neither useful nor realistic to consider the radiological protection of soil in abiotic isolation (see Fig. 4 in Part 1 for illustration).

As will be discussed further, there are three important aspects of a contaminated soil-plant system:

- (a) Surface radiation level which may directly irradiate local personnel occupying or working on the land;
- (b) The presence of radionuclides directly intercepted by the crop (or pasture) during fallout which might, very soon, become food or feed;
- (c) Transfer of the radionuclides by later crop uptake from the soil and, thereby, to future food intake by local or distant populations, or transfer by surface erosion to other soils, crops or water.
- (d) Some transfer of radionuclides, as with agrochemical residues, could occur as a result of "re-

suspension" by surface-eroding wind or water but this would represent a relatively "minor pathway" within the exposed ecosystem (see also last part of Section 2.5.4).

It is in relation to (c) that an appreciation of nutrient cycling becomes important, as discussed below.

2.2.3 Cycling of plant nutrients and fertilization

Under constant cropping and removal of the entire crop there is a constant drain of soil nutrients as illustrated in Table IV (based on 92; 141).

TABLE IV

Removal of elements from soil by the annual harvest of 4 tonnes of wheat grain dry matter per hectare. (only gross removal with no return via manure etc.)

Element (chemical symbol)	Removed kg ha ⁻¹ yr ⁻¹
Nitrogen (N)	105
Potassium (K)	18
Phosphorus (P)	15
Sulphur (S)	8
Magnesium (Mg)	6
Chlorine (Cl)	3
Calcium (Ca)	2
Sodium (Na)	1
Iron (Fe)	0.2
Manganese (Mn)	0.2
Zinc (Zn)	0.2
Copper (Cu)	0.03
Boron (B)	0.02
Cobalt (Co)	0.001

Note: In U.K. farming generally, it has been indicated that removals from soil of the trace elements selenium (Se), iodine (I), and molybdenum (Mo) lay within the range of approx. 0.000025-0.0125 kg ha⁻¹ yr⁻¹ (141).

The cycling of mineral nutrients and plant uptake in agroecosystems have been authoritatively reviewed and tabulated elsewhere (139; 141; 142). The agricultural significance of these removals will clearly depend upon the rate of natural replacement (e.g., by biofixation, dry deposition), by the mineral content of irrigation water, and by fertilizer applications. The significance here is owing to the fact that radionuclides tend to behave as their non-radioactive chemical relatives. Thus, cesium-137 often behaves like potassium, strontium-90 as calcium. When the radionuclide is an isotope of the natural soil element then its behaviour will be effectively identical (subject, of course, to any necessary chemical modification to the plant-available form), thus iodine-131 or manganese-56 will respectively behave as the natural elements. Plutonium-239, on the other hand, is an artificial nuclear reactor activation product and will behave uniquely. These considerations have important implications for the use and reclamation of contaminated soils (see Section 2.7).

2.3. Sources and nature of radioactive contamination

[2.3.1 Naturally occurring radionuclides](#)

[2.3.2 Anthropogenic radionuclides](#)

[2.3.3 Trends since 1945](#)

[2.3.4 Post-'Chernobyl' fallout over soils](#)

2.3.1 Naturally occurring radionuclides

For the purpose of detecting and monitoring for any increase or changes in soil radioactivity as a result of an accidental or planned release, of time, or of deliberate counter measures, the pre-event or effective 'base-line' levels must, of course, be known as indicated in Part 1. This level will be due to cosmogenic and primordial radionuclides naturally present (natural background level) and to anthropogenic additions during the 'atomic energy era'. These levels will depend upon the nature of the soil and to exposure to fallout, etc.

The 'base line' level must not be confused with the instrumental 'background' level of the particular detector and counting assembly used. This 'background' level will be the level indicated in the presence of a 'dummy' sample devoid of detectable radioactivity. This background of 'extraneous counts' will be due to possible electronic noise, the traces of radionuclides inevitably present in the structure of the detector, lead 'castle' or other radiation screen, incidental incoming cosmic rays, etc. (143).

Potassium-40 is the most significant of the natural radionuclides in 'average' soils (6). The specific radioactivity of potassium-40 in natural potassium is 31 Bq g⁻¹ (6). Assuming a content of 2% of elemental potassium in 'average' mineral soil (139) of bulk density of 1.5 g cm⁻³ to a rooting depth of 20 cm, this corresponds to a level of potassium-40 in soil of the order of 2 x 10⁵ Bq m⁻². Likewise, on the basis of 2.5% biogenic elementary carbon in the soil and the known cosmogenic carbon-14 content of approx. 0.2 Bq g⁻¹ natural non-fossil carbon (13) there will be approx. 10 Bq m⁻² of carbon-14.

Natural tritium (hydrogen-3) will be, effectively, in steady-state equilibrium with the hydrogen of surface soil and water (13). Assuming the necessary soil 'field capacity' and average water content equivalent to 6 cm rainfall and known cosmogenic tritium level of 0.5 Bq/l of atmospheric water (13) the tritium content of the soil was estimated. All these estimates, together with other data (6), are summarized in Table V below.

Radon-222 (an isotope of the chemically-inert gas radon) is also included in Table V because in the confined air spaces of soil it will tend to accumulate to a steady-state level as a result of uranium-238 decay.

TABLE V

Estimated levels of radionuclides naturally present in mineral soil to rooting depth of 20 cm and of bulk density of 1.5 g cm⁻³

Radionuclide	Radioactive half-life	Radiation emitted	Radioactivity Bq m⁻²
Radon-222	3.8 d	α	3×10^{-1}
Tritium (hydrogen-3)	12.4 y	β 3/4	3×10^1
Carbon-14	5730 y	β 3/4	5×10^3
Radium-226	1600 y	α , β	1×10^4
Thorium-232	1 4 1010	α , β	1×10^4
Uranium-238	4.5 x 10 y	α	1×10^4
Rubidium-87	4.7 x 1010 y	β 3/4	5×10^4
Potassium-40	1.3 x 10 y	β 3/4	2×10^5
		Total of the order	3×10^5

2.3.2 Anthropogenic radionuclides

Significant additions of radionuclides to the environment commenced with the construction and operation of nuclear reactors from 1942 onwards. Above all, from the military use of two atomic bombs (based on U235 fission) in 1945, and the subsequent testing of nuclear weapons in the atmosphere. There have also been continuing discharges of relatively small amounts of radioactive wastes from the nuclear power industry, use of research reactors, and from the uses of radioactive substances in medicine, research and technology. Finally, there has been a number of relatively minor nuclear accidents (see Sections 1.3.2 and 2.7.6 below) involving the release of radionuclides into the atmosphere with subsequent fallout or release episodes into agriculture, forestry and fisheries.

Tables I and V summarize and characterize the more important natural and anthropogenic radionuclides which might be expected to be found in contemporary soil samples. Levels and relative proportions will vary greatly according to:

- Geologic origin and composition of the soil;
- History of exposure to radioactive fallout;
- Post-exposure history in terms of time, agricultural practices, erosion, leaching, and countermeasures designed to reduce contamination levels.

Fertilizer practice can affect the levels of naturally occurring radionuclides, especially the use of compound 'N-P-K' fertilizers. For example, the application of approx. 130 kg nitrogen, 45 kg phosphorus, and 155 kg potassium per hectare of potato crop would be typical in parts of Europe (137). This would add some 500 Bq m⁻² of potassium-40 to the soil surface, together with traces of uranium-238, radium-226, and thorium-232 if the phosphate component had been derived from the commonly used 'phosphate rock' mineral resources (8).

Only significant cosmogenic radionuclides are included in Table V. Anthropogenic and cosmogenic radionuclides now present in the environment have been fully tabulated elsewhere (6).

2.3.3 Trends since 1945

There have been some continuous and sporadic additions of anthropogenic radionuclides since the first atomic bomb test in New Mexico (U.S.A.) in 1945. This means that effective soil 'base--line' levels have varied upwards (with additions) and downwards (as a result of radioactive decay, erosion, leaching, etc.) but always above the pre-1945 'natural background' level. Moreover, the 'base-line' levels of soils must remain significantly above the natural 'background' level indefinitely because of long radioactive half-life and relative immobility in soils (e.g., of plutonium-239).

Environmental trends since 1945, together with their implied population radiation dose commitments, have been extensively studied and documented by UNSCEAR (13; 8). Of interest is that, before 'Chernobyl', fallout from the earlier testing of nuclear weapons in the atmosphere was continuing at detectable levels. For example, 1982-monitoring data (144) indicated the annual fallout over areas of the U.K. illustrated in Table VI which also show the influence of rainfall. Some accumulated 'base-line' levels in soil as estimated by the writer on the basis of data in the same report (144) are illustrated in Table VII. Accumulated levels of plutonium-239 and -240 in soils of North--West Italy, comparable with those of Table VII for the U.K., have recently been reported; likewise, higher levels in areas with higher annual rainfall (145). Similar levels for cesium-137 have also been reported for the Netherlands (146).

TABLE VI

Continuing fallout over the U.K. during 1982 from earlier nuclear weapons testing in the atmosphere

(144)

	West area	East area
Annual precipitation - cm	170	74
Addition of plutonium-239 + 240 - Bq m ⁻² , year	0.12	0.07
Addition of cesium-137 (U.K. generally) - Bq m ⁻² year	5	

TABLE VII

Accumulated 'base-line' levels in soils of the U.K. by 1982 (based on data of ref. 144)

	'Higher' rainfall site in West (Glynllfion)	'Lower' rainfall site in East (Bratof)
Plutonium-239 + 240 Bq m ⁻² (30 cm depth)	72 - 134	36 - 63
Americium-241 Bq m ⁻² (30 cm depth)	21 - 45	8 - 19
Cesium-137 Bq m ⁻² (30 cm depth)	2,100 - 7,770	780 - 3,000

The age of a particular fallout episode can be indicated by the changing ratio of two radionuclide activities when they are isotopes of the same chemical element. Their respective soil chemistry must, effectively, be identical so that slight changes as a result of chemical or physical fractionation can be neglected. Therefore, in the absence of significant interim additions the change in isotopic ratio will be a function of their different radioactive decay rates and of the lapse of time involved. The changing ratios for cesium and strontium radionuclides are indicated in Table VIII. The Cs-134/137 ratio has been used to distinguish between deposition from the 'Chernobyl' release and those of earlier releases (147; 146).

Table VIII

Change in radioisotopic ratios of fallout as time - origin indicator

Radioisotope pair	Time	Ratio
Strontium-89/90	0 days	1.000 (as set)
	28 days	0.68

	56 days	0.45
	365 days	0.007
Cesium-134/137	0 years	1.000 (as set)
	1 year	0.75
	5 years	0.24
	10 years	0.06

There now appears to be a need to determine and/or collect (possibly existing) data on 'base-line' levels of radionuclides in agricultural and forestry soils worldwide. At present, the apparently limited published or available data appear mainly to be those of countries with relatively sophisticated atomic energy programmes. However, as demonstrated by 'Chernobyl', a major release of radioactive material into the atmosphere can result in fallout on a major international, if not global scale. Under no circumstances is this observation intended to imply that fallout detected in future would, necessarily, have any agricultural or public health significance whatever.

2.3.4 Post-'Chernobyl' fallout over soils

Understandably, the accident prompted an immediate activation of the full environmental radioactivity monitoring potential worldwide and a still-continuing stream of reports and publications relating to national (e.g. 147; 149-155) and international (e.g. 88, 156; 158) fallout and radiation levels. As the first post-accident year drew to a close a study of these reports indicated, very briefly, the following conclusions (see also Part 1):

Within days of the accident fallout episodes over soils in many countries across Europe were recorded. In many areas levels were considered sufficiently high to prompt intervention at national and regional levels to obviate the possibilities of exposed and contaminated standing crops and livestock entering public food supplies. Fallout was detected up to many thousands of kilometers from the Chernobyl accident site, e.g. in Japan (153), U.S.A. (101) and in the Republic of China where it was estimated that up to 0.6% of the total Chernobyl iodine-131 emission had fallen (159). Cesium-134 and -137 were detected in snow as far north as Greenland (160). Strontium-89 and -90 were detected in fallout and at significant levels on pasture in Yugoslavia. Attention was drawn to the paucity of post-Chernobyl fallout data on these radionuclides, evidently due to the 'time-consuming radiochemical isolation' needed for their reliable assay (161). Detectable fallout was not evidently reported from the 'Southern hemisphere' (124).

Despite the wide range of fission and radioactivation products certainly emitted, two radionuclides have attracted conspicuous attention. These are iodine-131 and cesium-137. The short radioactive half-life of iodine-131 (8 days) eliminated its significance as a soil contaminant within weeks of deposition. Cesium-137 (half-life 30 years), on the other hand, will effectively remain in the soil for centuries and, according to its availability to crops or pasture (see Section 2.5.2), may present problems in some local areas for

some years into the future. Many other radionuclides were, indeed, detected and determined, incidentally, in the fallout spectrum such as silver-110m, but not at levels likely to be of radiological significance (15; 162).

Accumulated cesium-137 deposited over Europe in the first post-accident week varied from zero (e.g., southern Spain, Sicily), extensively in the range of 1,000-10,000 Bq m⁻² over western Europe, and in the range 10,000-100,000 Bq m⁻² and more in the U.S.S.R. Soil deposition outside the U.S.S.R. was, not surprisingly, highest in the nearer countries in the path of atmospheric drift. Levels reached 200,000 Bq m⁻² in some relatively local areas of Sweden (82).

The physico-chemical form of a radionuclide in fallout depends on the nature and magnitude of the accident, the particular radionuclide, atmospheric conditions during transport, local weather on deposition, and time between emission and deposition. Studies of atmospheric samples collected in Switzerland (152) showed that iodine-131 was mainly in the gas (vapour) phase while cesium-137 and ruthenium-103 were apparently ejected and persisted as particles, later becoming attached to aerosols which could grow by coagulation. The latter could account for the presence of distant 'hot particles', e.g., of ruthenium-103 collected in Austria (115). However, the explosive emission at Chernobyl of radioactive debris evidently also included physically-persistent 'micron-size uranium oxide fuel particles' carrying both fission and activation products (163).

Emission of the chemically-inert radioactive gases krypton-85 and xenon-133 would, of course, remain in the gaseous form and would not appear in the soil deposition. Most of the fallout on soil was associated with rainfall as 'wet deposition' (164) although cases of 'dry deposition' had been observed (88). Relatively soluble vapours, if not already chemically combined, would tend to be dissolved in the water of rain or snow (see Fig. 4 in Part 1).

Above all, Chernobyl confirmed that a major accidental release into the atmosphere can lead to significant radioactive fallout on a local, international and even global scale which, fortunately, can be detected unambiguously with enormous sensitivity at levels far below those of any conceivable biological significance. Post-accident meteorological and local weather conditions played a critical role in location and level of fallout. Observed deposition was closely related to precipitation events and to the well-known local variability of rainfall, e.g., between valley and hill. Fallout in Japan was found largely in rainfall (153), and the highest fallout report in the U.K. (>6,000 Bq m⁻²) was associated with 'exceptionally heavy rainfall' (147) during an unusually 'wet' year (165). Likewise, high fallout occurred during heavy thunderstorms in Europe (150). As stressed earlier these observations strongly indicate scope for a considerably improved and coordinated weather forecasting and monitoring network for giving some advance warning for agriculture of accident fallout episodes in future (see Section 1.2.4). The local variability of precipitation would also account for 'hotspot' deposition (not to be confused with 'hot particles' - see above) above local average levels as observed at various locations in Europe (158).

2.4 Biological significance of contaminated soils

[2.4.1 General considerations](#)

[2.4.2 Radio-ecotoxicology](#)

[2.4.3 Occupational and public health implications](#)

2.4.1 General considerations

International authorities have identified three phases in relation to the accidental release of radioactive material: The 'early phase' which includes the short time before the accident when a clear threat of a significant release has been recognized at the site; the 'intermediate phase' or critical post-release period which may dictate off site intervention in the interests of public health, etc.; and a final 'recovery phase' or the extended time to the point when a return to 'normal' conditions can be assumed (44; 205; 90; 81).

These phases have very important implications in relation to soil contamination and to the protection of soil-dependent products and communities. These are briefly indicated seriatim below. (They can be compared with the natural disaster 'warning', 'crisis', and 'rehabilitation' phases as a result of floods, hurricanes, drought, etc. recognized by FAO (Personal communication, M.F. Purnell, Land and Water Development Division, FAO, Rome).

Early Phase : It is here that, on the basis of responsible and prompt notification nationally or internationally, agricultural authorities could be alerted to fallout possibilities - especially in areas whose juxtaposition with nuclear installations indicated potentially high fallout (see Sections 1.1.5; 1.2.4 and 1.4.3).

Intermediate Phase: On the basis of an improved communication network extending to farm community level, coupled with an internationally coordinated nuclear and meteorological assessment, to give warning of likely fallout episodes. This would, surely, provide for possibly valuable anticipatory measures as earlier indicated (Section 1.2.4). Such measures would, of course, depend on appropriateness, practicability, and upon economic considerations.

Recovery Phase: At farm level this will involve local monitoring of soils, crops, and livestock so that, on the basis of established radioecology, any necessary extension of countermeasures could be planned and implemented.

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2.4.2 Radio-ecotoxicology

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The term ecotoxicology has been defined elsewhere (167). This part of the review is concerned with toxicity or potential toxicity as a result of the ionizing radiation emitted by radionuclides contaminating soil, crops, and livestock. The term radio-ecotoxicology is used to distinguish these effects from those of non-radioactive chemical residues or pollutants.

The detection of abnormal radioactivity in soil or environment implies the presence of one or more anthropogenic radionuclides as the free element or chemical compound. While their biological significance will be due to the emitted radiation, their behaviour will be due entirely to their chemistry or biochemistry (when present in living organisms). In the context of radio-ecotoxicology it is important to recognize two features:

Firstly, the chemical weight of a fallout radionuclide will, relatively, be extremely small since the reactor fission products and transuranium products (actinides) will be largely emitted in the isotopically pure or 'carrier-free' state.

Secondly, possible radiation effects will depend very much upon the physical environment after fallout. Thus, a particular contamination level of soil (conventionally expressed in becquerels per square metre (Bq m^{-2})) can have very different implications according to physical environment and, therefore, according to the time after deposition.

The chemical weight or mass of an isotopically pure radionuclide is readily calculated (133) for a given level of radioactivity (Bq) on the basis of its radioactive half-life, mass number, and the 'Avogadro' number as illustrated in Table IX. Some non-radioactive (stable) fission products also accumulate in the reactor core (11) but not in sufficient quantities to affect significantly the carrier-free condition of the emitted radionuclides.

The low concentrations implied by Table IX have important implications in relation to the decontamination of freshly exposed and harvested crops as discussed earlier (Section 1.2.4). A level of $10,000 \text{ Bq m}^{-2}$ of iodine-131 per square metre of mature cabbage at a harvest yield of, say, 100 t ha^{-1} (10 kg m^{-2}) would correspond to an average chemical concentration in the whole cabbage of some $2 \times 10^{-7} \mu\text{g kg}^{-1}$.

Clearly, a fresh deposit by radioactive fallout will, initially, rest largely on the exposed soil and above-ground crop surfaces. Personnel working or walking over the soil would, therefore, be maximally exposed to the radiation emitted directly from such surfaces or, indeed, to exposure by inhaling re-suspended soil dust although this would normally represent a 'minor pathway' (see Section 1.2.2). Likewise, the consumption of such exposed and freshly harvested food crops, or pasture by grazing livestock, would lead to maximal ingestion of the fallout radionuclides. However, with time or through deliberate

intervention the deposit will tend to move down the soil profile with natural leaching, irrigation, or admixture within the soil by weathering disturbances, ploughing, etc. (see Sections 2.5.5 and 2.7).

Radiation emitted from the deeper layers will be largely absorbed (self-absorbed) by the containing soil mass. Hence, with time there will be a continually diminishing fraction of the emitted radiation escaping from the surface (as distinct from any decline of radiation as a result of radioactive decay). Likewise, with time, diminishing fractions of the radioactive deposit will be taken up by the crop root system. The effects of vertical dispersion can be roughly indicated as follows:

TABLE IX

Mass of carrier-free radionuclide equivalent to a given level of radioactivity

Radionuclide	Principal naturally-occurring stable isotope and chemically-related isotope (in brackets)	Mass of radionuclide in kg equivalent to 3.7×10^{16} Bq (1 MCi)	Mass of radionuclide in pg equivalent to 1 kBq (1,000 Bq)
Tritium (H-3)	hydrogen-1 deuterium (H-2)	0,035	1
Carbon-14	carbon-12	180	5,000
Potassium-40	potassium-39	0.2×10^9	4×10^9
Strontium-89	strontium-88 (calcium-40)	0.035	1
Strontium-90	" "	7	200
Ruthenium 106	ruthenium-102 (iron-56)	0.3	8
Iodine-131	iodine 127 (bromine-79)	0 008	0.2
Cesium-134	cesium-133 (potassium-39) (rubidium-85)	0.8	20
Cesium-137	" "	10	250
Plutonium-239	no naturally-occurring isotope	16×10^3	0.5×10^6

Footnote: Radioactivity levels of 1 MCi and 1 kBq respectively typify the orders accumulating within the reactor core and as observed per square metre of soils from post-Chernobyl fallout. The first three

naturally-occurring radionuclides are included for comparison.

If the significant deposit consisted mainly of cesium-137 and iodine-131 (both beta-particle and gamma-ray emitters) then when, say, less than 20% remained in the top 10 cm of soil the entire beta emission would be effectively self absorbed by the soil and less than 10% of the gamma radiation would penetrate upwards through the surface (estimate based on ref. 168, p. 364).

It is for these and other (see below) reasons that a fresh deposit of, say, 5,000 Bq m⁻² of cesium-137 would represent a far more significant radioactive contamination level than the same deposit dispersed to a depth of 30 cm or more of soil. Indeed, while levels of this order prompted intervention in parts of Europe soon after 'Chernobyl' the pre-Chernobyl levels of cesium-137 accumulated since 1945 (mainly as the result nuclear weapons testing in the atmosphere) would be of the same order in many areas of Europe (see Table VII).

Radio-ecotoxicological considerations here raise wider questions than human health. For example, are there likely to be adverse radioactive fallout effects upon soil-dependent fauna and flora per se? In particular, adverse effects upon the vital microbiological transformations in soil such as those of nitrogen biofixation and mineralization and, indeed, in the mobilization of radioactive contaminants themselves (73, pp. 552-555) or upon plant life itself? It is well established that sufficiently high radiation doses are lethal to all known forms of life. Indeed, irradiation by sealed gamma-ray sources is a well established method of sterilization or selective tissue destruction in vivo (169).

Some review of the immense range of studies of biological effects in organisms other than man (e.g. 21; 62; 73-75; 77; 170; 183; 213-215) indicates the following:

Because of the enormous complexity and variety in habitat, morphology, biochemistry, physiology, and natural longevity of living organisms there are correspondingly large variations in the biological effects of ionizing radiation exposure. Likewise, the significance of these effects differs in the context of human health and welfare.

External irradiation of the skin of pigs led to somatic lesions (radiation burns, etc.) as in man (73, pp. 884-886). Iodine-131 in rats caused thyroid cancer, and inhaled cerium-141 and 144 induced lung cancer in rats (170, Vol. II, pp. 21-44). The lethal dose-50's for animals tend generally to be higher than those for man (e.g., see ref. 170, Vol. I, p. 119) and those for the smaller forms of life are much higher still. Insects are much less dependent than mammals upon cell-renewal systems (170, Vol. I, p. 103) and would, therefore, be relatively immune to the delayed stochastic effects observed in higher animals. In any event, the relatively short life-spans of rodents, insects and microorganisms, for example, imply that many low-dose effects of possible 'late' significance in man would be of no significance to many classes of wildlife (170).

Irradiation can cause genetic damage and accelerate mutation rate in insects with their implied 'hereditary' effects. Some experiments have indicated that low-dose irradiation of plant seeds and seedlings could

actually have beneficial effects (170, Vol. I, p. 141).

There was no evidence that present accumulated levels of fallout actinides (e.g. plutonium-239) as a result of nuclear weapons testing or from discharges by nuclear processing plants had any effect on soil microbiological nitrification. However, such effects might be expected at higher concentrations when inhibition could be due to chemical toxicity *per se* rather than due to the emitted alpha-radiation (73, pp. 667-673).

The relatively rapid emergence of strains of microorganisms, insects, and rodent pests, which have become resistant to previously effective chemical biocides is well recognized (135). Its increasingly serious implications for agriculture and human health now attract media attention (e.g., 171). The development of radiation-resistant microorganisms has been observed (76) which, likewise, suggests the ability of microbiological populations to adapt to higher than normal radiation levels.

When considering the possible effects of radiation on soil organisms and upon soil dependent flora and fauna it should be noted that all other living organisms than man and his immediate domestic animals are subject to the range of naturally inhibiting or lethal environmental stresses. Moreover, the gathering, hunting, cultivation and harvest of living organisms as human food have clearly been a condition of survival since the beginning of human evolution.

Earlier reviews (55, p. 28) have indicated that "the amount of radioactive contamination required to destroy or injure and so reduce the productivity of plants and animals is much greater than that which would render the resultant foodstuffs unsafe for human consumption; the ratio being several orders of magnitude in the case of radioactive iodine, strontium and caesium".

Against this background and because of public sensitivity to possible or imaginary radiation harm to man a consensus has emerged that "it is the impact on man" that would be "important rather than the effects on other components of the biosphere" (77, Vol. I, p. 1).

2.4.3 Occupational and public health implications

The considerations above indicate that, in the contamination of soils, possible effects on soil-dependent fauna and flora can be ignored in the present context. In considering the contamination of soils in relation to human health three situations can be recognized (for units, terminology, etc. see Sections 3 and 4):

(a) Initial deposits on soil and exposed crop surfaces leading to unacceptable levels of external radiation exposure and consequent absorbed radiation doses for farm personnel working or walking over the ground ('occupational' exposure) - see Fig. 3 for illustration.

(b) Deposits where external radiation can be neglected but where levels of direct crop or pasture contamination could lead to unacceptable levels of crop or livestock contamination for harvest as food, and for drink such as milk from dairy cattle grazing on directly contaminated pasture (problems of local

and public health).

(c) Significant levels remaining in or on the soil which could indicate the need for constraints on future crops or products as a result of plant uptake from the soil (problems of Local and public health?).

Significant radiation exposure as a result of a passing cloud of radioactive emissions or through the inhalation of radioactive dusts, aerosols, etc. would be unlikely to arise except in the vicinity of an extremely serious accident or because of some more distant but unusual weather condition (75). For example, in Sweden after 'Chernobyl' although ground deposits of $100,000 \text{ Bq m}^{-2}$ and more were recorded in some cases, doses from these external radiation sources were reported as "negligible" (82).

External radiation exposure from the soil and floral cover will, of course, depend upon a number of factors (see above), especially radionuclide composition of the fallout (and, therefore, upon the time of exposure after the fallout), upon the precipitation conditions at the time of deposition and afterwards, and upon the nature of the aerial biomass at the time of deposition.

These factors probably account for the different external radiation dose rates per becquerel per square meter implied in some of the post-Chernobyl reports. For example, in the Federal Republic of Germany (150) "top level" ground deposits of $100,000 \text{ Bq m}^{-2}$ representing an "absorbed dose" equivalent to $0.15 \text{ mrem per day}$ were indicated for persons "permanently on such ground". This would correspond to approx. $0.06 \mu \text{ Sv hr}^{-1}$. Data from Sweden, on the other hand, implied (82, pp. 4 & 10) that in the "regions of highest contamination" local levels of the order of 1 MBq m^{-2} (i.e., for iodine-131 and cesium-137) were reached and involved external irradiation dose rates of the order of $10 \mu \text{ Sv hr}^{-1}$, i.e., approx. $1 \mu \text{ Sv hr}^{-1}$ for a deposit of $100,000 \text{ Bq m}^{-2}$ (compare above).

Absorbed radiation dose equivalent rate for a person standing on ground contaminated by a significant deposit of gamma-emitting radionuclide can be measured with a suitable monitor (usually at the conventional height of one metre above ground level). Alternatively, it can be estimated by the application of an empirical equation to an already measured deposit in terms of Bq m^{-2} for one or more radionuclides. For estimating effective dose equivalent (EDE) commitments as a result of exposure to external ground or surface sources, dose rates must, of course, be integrated over an appropriate time into the future to indicate the total dose likely to be accumulated in that future (88, p. 16 and appendix; 80, pp. 27 et seq). The following equation relates dose rate and deposit:

$$\text{DR} = \text{SD}_M \times \text{CF} \text{ (Eq. 1)}$$

where DR is rate of absorbed dose equivalent in $\mu \text{ Sv hr}^{-1}$, SD_M the ground surface deposit in MBq m^{-2} (mega Becquerels per square metre), and CF the appropriate conversion factor for the particular radionuclide (80, pp. 27 et seq) as indicated below:

Radionuclide	Conversion factor
--------------	-------------------

Strontium-90	0 (No significant gamma-emission)
Iodine-131	0.75
Cesium-137	0.95
Ruthenium-106	0.35
Plutonium-239	0.004

Thus, equation (1) indicates a dose rate of $0.075 \mu \text{ Sv hr}^{-1}$ for a surface deposit of $100,000 \text{ Bq m}^{-2}$ (0.1 MBq m^{-2} of iodine-131 which can be compared with the data quoted at the bottom of the previous page. Integrated doses have been tabulated for continuous periods of 1 week, 1 year, and up to 50 years spent on the ground (81, pp. 56-57).

For the protection of personnel exposed to both significant external sources and as result of radionuclide intake by food and drink the total dose equivalent commitments might, of course, have to be considered additively (157) and associated derived intervention levels, or their application, modified accordingly (see above and Section 3).

2.5. Behaviour in soils and movement into foodwebs

[2.5.1 Effective 'disappearance' and redistribution](#)

[2.5.2 Uptake by crops](#)

[2.5.3 Scenario for movement into food](#)

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[2.5.6 Application of models to soil-food chain transfer](#)

2.5.1 Effective 'disappearance' and redistribution

Effective 'disappearance' from within the soil or from the soil surface deposit will depend upon radioactive decay on the basis of known half-life (see Table I and footnotes), surface erosion and possible volatilization, leaching and other transport down the soil profile, and removal by plant uptake and harvest. There is an immense literature on these aspects which can be no more than illustrated here (e.g., see 62; 77; 59).

Uptake of soil radionuclides will depend upon the radionuclide, its chemical concentration (not upon the level of radioactivity), its chemical form, the presence and availability of natural isotopes of the same element, its distribution down the soil profile, its availability to the plant root system, plant, and plant growth status.

As explained above the chemical concentration of the radionuclide will be extremely low. Therefore, initially, it is likely to be relatively firmly held at abiotic adsorption sites on the basis of the well-known mechanisms of adsorption (172; 166) and movement by solution into soil water and loss by volatilization from the surface will likewise tend to be relatively slow. However, effective chemical concentration of the radionuclide will also depend on the presence and availability of naturally-present isotopic element, but those of the fallout radionuclides are also relatively small as illustrated in Table X (from data of ref. 77). Natural elements of the actinides (plutonium, americium, etc.) do not exist. 'Availability' and movement of the radionuclide will also be greatly influenced by the presence of chemically-related elements and their 'availability', e.g. Cs-134 and -137 by available potassium, Sr-89 and -90 by available calcium (see Tables I X and XI).

TABLE X

Reported concentrations in soils and plants of naturally occurring elements of fallout radionuclides $\mu\text{g.g}^{-1}$ dry wt (from ref. 77)

Soils	Cesium 0.3 - 25 "Average" - 10	Iodine 5	Ruthenium < 10⁻³	Strontium 50 - 1,000 "Average" - 300
Plants:				
Fungi	23	-	-	300
Flowering plants (Angiosperms)	0.2	0.4	5 x 10 ⁻³	26
Cereals	-	0.1	-	-
Wheat straw	-	-	-	10-50
Wheat grain	-	-	-	4-10
Grass	<2 x 10 ⁻²	0.8	-	50-60
Vegetables	-	0.1-0.8	-	-
Various species	2 x 10 ⁻³ - 1	-	-	-

Note: A useful and comprehensive review of micronutrient elements and their distributions in soils worldwide is available (173).

However, raising the effective concentration of the fallout radionuclide by these mechanisms of 'isotopic dilution' and chemical mixing will require time, availability, and the necessary mobility in solution or by dry diffusion.

In short, raising the 'effective' chemical concentration (other things being equal) will tend to reduce the proportion of radionuclide taken up by the plant root system, and increase its availability to move down the soil profile by leaching as a result of de-adsorption. The behaviour of radionuclides in the soil-plant system as a function of concentration, soil pH, etc. has been reviewed by Scott Russell and his colleagues (53, pp. 89-124).

For the reasons indicated above, except for short lived radionuclides such as iodine-131, the "disappearance" from, and movement within soils, tend to be slow. The persisting levels of much earlier fallout illustrated in Table VII are not, therefore, surprising. Nor would they be more than marginally accounted for by the continuing and detectable fallout before 'Chernobyl' (see Table VI).

Studies in Switzerland (150) indicated that cesium-137, deposited as a result of the atmospheric testing of some 500 atomic and hydrogen bombs during the 1950s and '60s, sank "only a few millimetres each year". Strontium-90 is "bound in the earth more weakly and is now up to 30 cm deep". This slow movement does have the advantage of lessening the possibility of groundwater pollution.

Many studies have been made of the "availability" of radionuclides deliberately added to representative soil types. Some data are illustrated in Table XI.

TABLE XI

"Available" fractions of radionuclides in different soils after 6 months (from ref. 73, pp. 660-662)

	Soil type			
	Clay	Loam	Sand	Peat
Soil characteristics				
Organic carbon - %	5.2	1.6	1.2	35
pH (in 0.01 M CaCl)	5.7	7.1	6.1	5.9
C.E.C. meq/100 g	39.6	15.2	10.4	132.9
Water content at 100 cm tension - g/100 g soil	52	29	11	90
Radionuclide in "available" phase (water-soluble + exchangeable + organic, etc.):				
Cesium-134	5%	5%	10%	40%
Strontium-85	85%	85%	85%	70%
Americium-241 (actinide)	< 4%	< 4%	< 4%	< 4%

Note: Other isotopes of the same element (e.g., Cs-137, Sr90) would, of course, give the same results.

Although ruthenium-106 can exist in anionic or cationic forms in soil the major fraction tends to be "strongly" fixed and, like cesium, moves downwards only a few millimetres per year (77, Vol. I, pp. 280-281). Strontium-90 is largely held at exchange sites in the soil so that movement tends to be greater in soils which are high in organic matter or in the chemically related calcium (77, Vol. I, p. 98; see also Section 7.3). Cesium-134 (and 137) are influenced by the "form of vegetation overlying the soil". In the presence of a litter horizon a high proportion would be bound, and movement by leaching or erosion would be small (77, Vol. I, p. 326; see also Table XI).

The major source of plutonium-239 (and its other isotopes) in contemporary soils is from the earlier atmospheric testing of nuclear weapons. For example, no plutonium-239 was detected in Switzerland from the Chernobyl fallout (150). Plutonium isotopes can show relatively high mobility in acid or alkaline soils depending on clay and chalk content. Physical adsorption of plutonium in soils can be reversed by uranium addition. More than 90% of plutonium in soils would be expected to become rapidly adsorbed by clay particles (77, Vol. IV, pp. 1-7); see also americium data in Table VIII).

A major factor in the movement of deposited radionuclides into soils will be ploughing (see Section 2.7.3), hence the difference observed in the distributions of earlier deposits between pasture and cultivated land. However, ploughing will not, necessarily, affect plant uptake (77, Vol. I, pp. 17-18).

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2.5.2 Uptake by crops

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Except in cases of very high contamination by fallout the significance of soil contamination will be almost entirely owing to the associated or resulting contamination of crops, pasture, and, thereby, possible movement of radionuclides into foodwebs and the human diet.

Two mechanisms need consideration:

- Direct interception of the fallout by aerial biomass of the plant;
- Uptake from the soil through the plant root system.

Above ground interception

The interception factor (r) is defined as the proportion of total (wet + dry) deposition retained by the aerial biomass as follows:

$$r = 1 - e^{-\mu Y_v} \quad (\text{Eq. 2})$$

where μ = the "absorption coefficient" expressed in $\text{m}^2 \text{kg}^{-1}$ dry weight of aerial biomass while Y_v = dry weight density of aerial biomass expressed in kg m^{-2} of soil area.

Equation (2) implies that r must lie between 0 and 1. Clearly, the absorption coefficient will be higher for leafy vegetable (e.g., cabbage) than sparsely-leaved crops (e.g., tomato or onion). Moreover, it is important to note that while most of freshly harvested vegetables might be consumed, only the fruits of tomato plants, nut and pome trees, etc. would be consumed.

The value of r tends to vary as follows:

Wet deposition > dry deposition

Dry deposition on wet grass > dry deposition on dry grass

Small particulate deposition > large particulate deposition

The interception factor has been especially applied to pasture grass where yields in the range of 0.25-1.0 kg dry weight m^{-2} might be expected and μ has been assigned the value of $2.8 \text{ m}^2 \text{kg}^{-1}$ (77, Vol. I, p. 21; 13, p. 331).

It follows that these grass yields respectively imply corresponding interception factors of 0.5 and 0.9. In short, at high yields there would be high interception. However, it is obvious that weather conditions could also play an important role in practice. For example, a fallout episode followed by continuous but uncontaminated rainfall would move a higher proportion into the soil than one followed by dry weather.

The important implication of interception is that the harvest of recently exposed vegetable, fruit crops, etc. could lead to a relatively high dietary intake. This, indeed, accounted for extensive constraints across Europe, soon after 'Chernobyl', on the consumption of fruit and vegetables, and upon the use and movement of cattle grazing over contaminated pasture (174; 175; various post-accident press reports, etc.).

Forest cover would also be associated with high interception (77, Vol. I, p. 23) but relatively small proportions would be likely to become absorbed by fruit, nuts, etc. Much of the fallout intercepted by conifers was expected to become ground litter after 'Chernobyl' (14). The possibility of high interception of longer-lived gamma-emitting radionuclides (e.g., cesium-134 and 137) by timber stands for paper pulp, and, possibly, become a source of external irradiation to readers of the printed paper does not appear to have been investigated.

There is evidence that under conditions of prolonged fallout most of the activity of herbage would be due to foliar uptake rather than from the soil (77, Vol. I, p. 23; 59, pp. 5-6).

Root uptake. Uptake through the root system has also been the subject of wide ranging studies which illustrate enormous variability (77, Vol. I, pp. 137-150 & p. 331; 176) and, therefore, the difficulty of establishing reliable models. This notwithstanding, "it now seems to be standard practice during the estimation of the extent of radionuclide uptake by plants to adopt a single transfer ratio of plant activity/soil activity" (77, Vol. I, p. 26; 177, pp. 295-318).

The "standard transfer factor" (TF_S) has been defined as:

$$TF_S = \frac{\text{radionuclide activity kg}^{-1} \text{ dry wt. of product (Bq)}}{\text{radionuclide activity kg}^{-1} \text{ dry wt. of soil (Bq)}} \dots\dots (Eq. 3)$$

as measured under 'standard conditions' involving the top 10 cm of soil under grass and top 20 cm for other crops, organic matter content of 10% for grass, 4% for other crops, soil pH of 6, total contamination period of 2 years.

The actual TF value (TF_A) has been related to TF_S as follows:

$$TF_A = TF_S \cdot e^{(pH-6) \cdot a} \cdot e^{(OM-4 \text{ or } 10) \cdot b} \cdot e^{(D-10 \text{ or } 20) \cdot c} \cdot e^{(y-2) \cdot d} \dots (Eq 4)$$

where OM is organic matter-%, D is soil depth-cm, y is contamination period-yr. The 'correction factors' a, b, c and d vary according to the radionuclide and class of crop and have been tabulated elsewhere (178).

Some values are illustrated below:

Some correction factors for equation - 4 (from 178):

	- cereals, fodder and grass			
	a	b	c	d
Cesium isotopes	- 0.87	+ 0.030	- 0.12	- 0.027
Strontium	- 0.84	+ 0.057	- 0.050	- 0.006
Plutonium	+ 0.058	+ 0.011	- 0.240	+ 0.050

	- green vegetables and potatoes			
Cesium	- 0.540	- 0.024	- 0.030	- 0.100
Strontium	- 0.820	+ 0.201	- 0.004	- 0.018
Plutonium	+ 0.330	+ 0.011	- 0.150	- 0.4?0

Equation (4) provides for adjustment of TF on the basis of differences between the conditions of their measurement or application and those defined as "standard". A useful summary of "standardized" TF values has been prepared for cesium-134/137 (146; see also Table XII).

Combined mechanisms of uptake. Crop contamination may involve simultaneous uptake from the soil via the root system and from continuing fallout by interception. Soil-plant TF values can be measured under sheltered conditions to eliminate interception. Alternatively, the difference in isotopic ratio (see Section 2.3.3) between the aged radionuclide in the soil and the corresponding ratio of the newly intercepted fallout may be a sufficient indicator (e.g., 59, p. 6). Recognition of the combined effects can be important. Thus, apparent TF values for plutonium-239 under the conditions of continuing fallout (e.g., in the proximity of a nuclear processing plant) were of the order of 2×10^{-2} . However, when uptake only occurred from the soil TF values of 5×10^{-4} were obtained (77, Vol. IV, p. 34).

There is a large body of data on transfer factors based on studies with soils contaminated by the earlier nuclear weapons test fallout or by the experimental addition and mixing of known levels of radionuclides in the test soils. A few data are illustrated in Table XIII (based on ref. 144) and Table XIV (based on ref. 179).

TF values are usually expressed as ratios on a dry weight basis for soil and plant. However, it is often useful to convert TF values for the wet weight of product as would be harvested, retailed fresh, or consumed, while still retaining the dry weight basis for the soil (146). For this purpose note:

$$\text{TF (wet plant weight basis)} = \text{TF (dry weight basis)} \times \frac{(100 - \text{MC})}{100} \quad \text{.. (Eq.5)}$$

where MC is the %-moisture content of the plant product.

A wide range of TF values under 'standard conditions' for the radionuclides Am, Co, Cs, Mn, Np, Pu, Ra, Sr, Th, U, Tc, and Zn for sandy, loamy and clay soils have been tabulated (178); likewise an extremely comprehensive collection of related data (77, Vol. VI).

Some TF values under standard conditions (from ref. 178) are compared in Table XII below:

TABLE XII

Some 'standard' soil-plant transfer factors (TF_S) (from ref. 178, pp. 11 & 12)

		Radionuclides		
Soil type	Crop type	Cs-134, 137	Sr-89, 90	Pu-238. etc.

Sandy	Grass	0.041	0.086	4.6 x 10 ⁻⁵
	Green vegetables	0.098	0.092	-
	Tubers (potatoes, etc.)	0.028	0.055	1.1 x 10 ⁻³
	Cereals	0.016	0.090	5.6 x 10 ⁻⁵
Loamy	Grass	0.037	1.8	3.0 x 10 ⁻⁵
	Green vegetables	0.073	2.2	-
	Tubers	0.021	0.13	3 x 10 ⁻⁴
	Cereals	0.014	0.19	3.7 x 10 ⁻⁵
Clay	Grass	0.12	1.2	2.1 x 10 ⁻⁵
	Green vegetables	0.048	1.1	-
	Tubers	0.014	0.066	2 x 10 ⁻⁴
	Cereals	0.011	0.13	2.6 x 10 ⁻⁵

Note: See Tables XIII and XIV for additional data on Pu isotopes. See equations 3 and 4 for adjusting to non-standard soil conditions. Use equation 5 for calculating TF values on 'wet weight' basis; for this purpose a moisture content of about 20% can be assumed for harvested cereals, 75% for other crops.

TABLE XIII

Transfer factors determined with soils (dry wt. basis), plants (fresh wt.) in U.K. contaminated by fallout from nuclear weapons testing (from 144)

Crop	Radionuclide	Location (see Tables VI and VII)	
		Glynllifion (<i>'Wet'</i> westerly area)	Bratofth (<i>'Dry'</i> easterly area)
Wheat	Cesium-137	0.030	0.3
Potato	"	0.081	0.09
Wheat	Plutonium-239 + 240	0.004	0.01
Potato	"	0.0017	0.0066

Note: Moisture content of wheat 20-25%, potato 70-80% (for Eq. 5).

TABLE XIV

Transfer factors determined with experimentally contaminated soils typical of EC countries (from 179)

Soil characteristics:			
	Soil - I	Peaty soil	OC - 35%

			OM - 58%
	Soil - II	Well drained sandy soil	OC - 1.2%
			OM - 2.9%
	Soil - III	Well drained loam	OC - 1.6%
			OM - 4.2%
	Soil - IV	Poorly drained clay	OC - 5.2%
			OM - 12.8%

Transfer factors (dry wt. basis)				
		Radionuclide		
		Plutonium-239	Cesium-137	
	Soil - I	Cabbages (outers)	0.27×10^{-4}	0.46
		Potatoes (flesh)	0.13×10^{-4}	0.19
	Soil - II	Cabbages (outers)	1.0×10^{-4}	0.02
		Potatoes (flesh)	0.42×10^{-4}	0.08
	Soil - III	Cabbages (outers)	8×10^{-4}	0.025
		Potatoes (flesh)	0.5×10^{-4}	0.035
	Soil - IV	Potatoes (flesh)	0.8×10^{-4}	0.09

Note: OC = Organic carbon, OM = organic matter. Moisture contents of freshly harvested cabbage or potato would be expected to be in the range of 70-80% (re equation 5).

The many plant uptake studies (see especially 62; 73-77; 59) suggest some general conclusions. For example:

Cesium-137 tends to accumulate in certain but not all species of fungi, including edible species. Lichens, mosses, etc. tend to accumulate and to retain relatively high levels of fallout radionuclides as a result of their shallow soil or equivalent matrices with corresponding higher movement into the dependent fauna, e.g., grazing, reindeer (184).

The plant uptake of the relatively radiotoxic actinides tends to be very low (e.g., see Tables XI to XIV).

It can be assumed that approx. 10% of iodine-131 in soil is available for plant uptake but has limited radiological significance because of its short radioactive half-life (77, Vol. III, p. 324).

The stage of plant growth can be very important in a fallout episode. E.g., "Cereals will be most affected if there is deposition between ear emergence and harvest as floral contamination can then occur" (59, p. 82).

Many of the soil-plant transfer data show great variation, including instances where TF values may greatly exceed unity and suggest bioconcentration in the plant (e.g., of radiostrontium - see ref. 77, Vol. I, pp. 137-150). They also indicate some possibly important anomalies, e.g., higher TF values determined after fallout deposition than those determined under experimental conditions (176).

As would be expected, uptake depends upon species and variety - other things being equal. For example, more strontium-89/90 is taken up by legumes than by fruit or cereal crops (77, Vol. I, p. 126).

2.5.3 Scenario for movement into food

TF values (see above and Section 2.5.4 below) have been used for some conservative estimates (i.e., conservative on the basis of a given deposit), by the writer, of dietary uptake of cesium-137 in the immediate years after "Chernobyl" on the basis of earlier data and assumptions (e.g., 88 and associated appendix) as follows:

- (a) Effective total soil deposit (SD) from fallout = $10,000 \text{ Bq m}^{-2}$ (cf. Section 2.7.1);
- (b) Effective weight of dry soil (W) in crop root zone - 250 kg m^{-2} ; or 50 kg m^{-2} for pasture.
- (c) Effective soil contamination level in root zone (SC) = $(SD)/(W) = 40 \text{ Bq kg}^{-1}$ or 200 Bq kg^{-1} for pasture.
- (d) Average "food basket" for "central Europe" applicable;
- (e) Lake or reservoir water contamination level (WC) at effective average weight of $5,000 \text{ kg water m}^{-2} = 2 \text{ Bq kg}^{-1}$, i.e., $10,000/5,000$ (it is likely to be lower because of adsorption and sedimentation factors, but, in the case of cesium-137, possibly not very much lower (see ref. 77, Vol. I, pp. 389 et seq.).

The contamination level (CL) of basket commodity is given by the equation (Cf. equations 3, 4 & 5 above):

$$\text{CL} = \text{TF (fresh weight basis)} \times \text{SC}$$

Additionally, the following relationships have been adopted (see ref. 88, appendix and Section 1.2.2 of Part 1 for fish/water bioconcentration factor):

$$\text{CL (cow's milk)} = 0.6 \times \text{CL (grass or fodder)}$$

$$\text{CL (beef)} = 1.5 \times \text{CL (grass or fodder)}$$

$$\text{CL (lamb meat)} = 15 \times \text{CL (grass or fodder)}$$

$$\text{CL (goat's milk)} = 3 \times \text{CL (grass or fodder)}$$

$$\text{CL (goat meat)} = 7 \times \text{CL (grass or fodder)}$$

$$\text{CL (lake fish)} = 1,000 \times (\text{WC})$$

CL (drinking water) = WC (Contamination level of reservoir- derived drinking-water and that of exposed fisheries assumed to be identical, i.e., 2 Bq kg^{-1} . That of the ICRP "standard man" is assumed below for the annual intake of drinking water - see ref. 19).

Results of estimates based on the above assumptions and upon the higher TF-values variously reported are indicated in Table XV below. Comparably-related orders of contamination levels following a specified deposit of cesium-137 have been indicated elsewhere (123, p. 170).

More sophisticated models have been used for developing dietary intake scenarios following a single "spike" fallout episode or under the conditions of "continuous uniform" fallout (79; see also Section 2.5.6).

TABLE XV

Conservative scenario for post-' Chernobyl ' dietary intake of cesium-137 in 'Central Europe' (estimate by author)

Basket commodity	TF (fresh wt.) (Eq.5)	CL Bq kg⁻¹	"Average" food intake per capita kg yr⁻¹	Intake of Cs-137 per cap. Bq yr⁻¹
Green vegetables	0.1	4	50	200
Cereals	0.04	1.6	100	160
Potatoes	0.025	1	100	100
Grass/fodder	0.025	5	--	--
Cow's milk	--	3.0	200	600
Beef	--	7.5	50	400
Fruits	0.025	1	20	20
Pulses	0.05	2	20	40
Goat's milk	--	14	20	300
Lamb meat	--	75	10	750
Lake fish	--	less than 2,000	10	less than 20,000
Drinking water	--	less than 2	800	less than 1,600

Application of the appropriate radiation dose conversion factors in terms Sv Bq⁻¹ (e.g., see refs. 181; 182; also Section 3.1) indicates the average effective dose equivalent (EDE) commitment. Thus, the total Cs-137 intake indicated above corresponds to an EDE of less than 0.4 mSv for that year of intake on the basis of a radiation dose conversion factor of 1.5×10^{-8} Sv Bq⁻¹ (182, Part 1. Suppl., pp. 236 & 237). The relatively high potential contributions from lake fish and drinking-water should be noted. It should also be noted that the estimates above neither take into account pre-Chernobyl base-line levels of soil Cs-137 (see above), nor the possibility of some post-'Chernobyl' direct crop interception of further fallout or dry deposition of contaminated soil particulates. The scenario above illustrates the nature of the problems involved when estimating dose equivalent commitments as a result of radionuclide intake as food and drink (see also Sections 2.5.4; 3 and 4).

Finally, while such projected EDE values can indicate the suitability of a soil for continuing or modified agriculture or, likewise, the suitability of water for fisheries - such indications are no substitute for on-site monitoring in emergency situations as already stressed (Section 1.2.3).

In relation to the scenario depicted in Table XV above it may be noted that a ground deposit of $50,000 \text{ Bq m}^{-2}$, for example, would have implied an average dose commitment of 2 mSv for that year of intake. On the basis of the "long-term" post-Chernobyl dose intervention level (see Section 3) of 1 mSv adopted in Sweden (82) this would, then, have indicated the need for intervention by constraint on fish consumption. Moreover, if the higher dose conversion factor of $10^{-7} \text{ Sv Bq}^{-1}$ were adopted, as was the case in Sweden (ref. 82, p. 8) on the basis of 1-year old infants being the critical population group, such constraint at lower levels of ground deposit would, accordingly, have been indicated (see Section 3.1).

2.5.4 Movement in foodwebs

As indicated earlier (Section 2.4.2), when human health is adequately protected, radiation effects on soil-dependent wildlife may, indeed, be of interest but unlikely to be of concern under the conditions of an accidental release (183; 213).

The movement of radionuclides in foodwebs per se does not lie within the scope of this review but certain aspects are relevant here. A classic and still useful review of this subject was prepared many years ago by Scott Russell and his colleagues (53).

The significance of plant or grazing livestock uptake by direct interception or indirectly from the soil through crop, pasture or livestock drinking water will depend upon time, and upon post-harvest and beyond-farm gate treatment. Thus, food processing may involve washing, milling and extraction of cereals, dilution with uncontaminated products, etc. Drying and concentration processes, on the other hand, (e.g., for milk powder and concentrates) may involve a corresponding concentration of the radionuclide which may or may not be reversed before human consumption (see Table IV and Sections 3.1 and 3.3). The time factor will largely eliminate the significance of short-lived radionuclides (e.g., iodine-131, manganese-56) in processed or stored foods, even when prepared from products harvested immediately after fallout. Likewise, each stage of the food chain or web will also be likely to result in reduction on transfer. This reduction can be very high. Thus, the movement of ruthenium-106 through the pasture-cow-milk-man chain was very low, less than 0.1% being absorbed through the rumen of the lactating cow and less than 0.002% being secreted in the milk (77, Vol. I, p. 297). In any event, these problems would be the responsibility of the food industry and public health authorities. However, in aquatic foodwebs, transfer may involve bioconcentration (see below).

There may be problems for local communities living more directly "off the land", and for local communities in 'developing' countries where land might be exposed to the fallout from an out-of-state release and where there may be no technical infra-structure for the detection and monitoring of fallout and its possible health significance (see also Section 1.1.5 in connexion with 'maps').

In Sweden, wildlife (fish, reindeer)-dependent communities were seriously affected by 'Chernobyl' fallout on account of high movement into reindeer and bioconcentration by fish of inland lakes (184). Here, however, a monitoring infrastructure existed and was rapidly mobilized (82). The movement of strontium-90 and cesium-137 in the food chain lichen-reindeer or caribou-man has been especially studied in relation to Lapp communities (59, p. 145).

Of interest here is a post-'Chernobyl' report (185) that pickling in brine of Cs-137 contaminated meat successfully reduced levels in the meat proper from 570 Bq kg^{-1} to 70 Bq kg^{-1} (i.e., by more than 85%) after three weeks.

The term "transfer coefficient" (F_m) has been introduced (186) for relating radionuclide concentration in milk (Bq kg^{-1}) to the daily feed intake of a lactating cow. Using the terms defined above (section 2.5.3):

$$F_m (\text{day kg}^{-1}) = \frac{\text{CL (cow's milk - Bq kg}^{-1})}{\text{CL (grass / feed - Bq kg}^{-1}) \times \text{Daily intake (kg grass / feed day}^{-1})}$$

A mean steady state value of 0.004 was assigned (186) to F_m for cows fed alfalfa contaminated by fallout cesium-137. Since 50 kg day^{-1} would be a high (wet weight) intake rate (Comer in ref. 53, pp. 127-156), the above equation implies a factor of 0.2 in the relation used on in Section 2.5.3 and confirms the 'conservative' nature of the factor 0.6 adopted for the 'scenario' above.

The F_m concept was developed as a less variable transfer coefficient for radionuclides in the feed - milk step of the food chain over the longer periods of time when milk and tissue radionuclide concentrations had "equilibrated". Reference has been made to some of the problems of decontaminating freshly harvested fruit and vegetables, and to the effects of food processing "beyond the farm gate" in Section 1.2.4.

Contamination of inland fisheries would result from direct fallout. There could also be transfer from contaminated surface soils by erosion and run-off in river and lake catchments. The accumulation and bioconcentration by fish can be high. For example, of cesium-137 in oligotrophic lakes (77, Vol. 1, pp. 389 et seq.). Bioconcentration of cesium-137 decreased with increasing concentration of natural potassium in water. It was concluded that a bioconcentration factor of 1,000 for cesium should generally be assumed for the food chain freshwater lake-fish-man (21, pp. 473-481).

The possible transfer from catchment soils to inland fisheries will, clearly, depend upon erosion, post-fallout precipitation and run-off. Radioactive particulates will, therefore, tend to have become exposed to water before reaching the water body and retain contamination until sedimentation (71).

Finally, in this Section, if there be a short period of high radionuclide intake by a local community as a result of using freshly harvested exposed vegetables, etc. this is likely to represent a single input. Under these circumstances the "effective half-life" of the absorbed radionuclide (see footnote to Table I) would be very much less than the radioactive half-life. Thus, the effective half-life of cesium-137 (radioactive half-life - 30 yr.) in man would be expected to lie between 45 and 135 days for "most individuals" after the cessation of input (77, Vol. I, p. 375; see also footnotes to Table I).

2.5.5 Leaching

While any biological effects of a radionuclide will be due to the emitted radiation, leaching down the soil profile will be a matter of its physical-chemical form. The quantitative study and prediction of radionuclide behaviour parallels that of chemical solutes, e.g., of fertilizer-derived nitrate (92). However, the study of radionuclide leaching is facilitated by the ease and sensitivity by which it can be instrumentally followed.

Methods for the quantitative study and modelling of radionuclide migration down the soil profile under conditions of leaching have been usefully discussed and compared by Bachhuber et al. (72) as briefly summarized below:

The critical parameter in the migration of a radionuclide (or any solute) down the soil profile with water infiltration is the "retardation factor", R (reciprocal function of the R_f value in partition chromatographic analysis), defined as:

$$R = W/N \text{ (Eq. 6)}$$

where W is the average net downward migration velocity of the pore water, and N that of the radionuclide.

In the dynamic method, R is determined experimentally with columns of soil. In the static method, R is calculated on the assumption that the chromatographic type partition of radionuclide between mobile water phase and solid soil phase (i.e., by reversible sorption) is applicable. The chromatographic type "distribution coefficient", K , is defined as:

$$K \text{ (cm}^3 \text{ g}^{-1}\text{)} = \text{Bq g}^{-1} \text{ soil Bq cm}^{-3} \text{ pore water (Eq.7)}$$

and:

$$R = 1 + d.K/V \text{ (Eq. 8)}$$

where d is the bulk density of dry soil and V the volumetric water content. Measured radioactivities in Bq are, of course, adjusted for significant radioactive decay between measurements.

In the fallout method R is calculated by applying a conventional model to the distribution observed in the soil profile after the known period of time since the effective deposition by fallout.

These three methods were applied to 'ranker, podsol, and cambisole soils (FAO classification) to obtain the comparative values of K for the different horizons of each soil. For the dynamic and static methods, carrier-free strontium-85 and high-specific-radioactivity cesium-137 were used in the presence of tritium-labelled water as a water-front and--movement tracer. The fallout method was applied in 1978 to the residual strontium-90 and cesium-137 in the same kinds of soil exposed to the much earlier nuclear weapons testing fallout.

A few data for the cambisole are illustrated in Table XVI (from 72). The respective average migration rates (estimated from the original data by the writer) for strontium and cesium roughly parallel the respective values of 1.7 and 1.0 cm per year given by the original authors (72) by their fallout method and imply an average effective (or excess) rainfall in respect to infiltration of cat 40 cm per year in the top 9-cm horizon under the field conditions after fallout. These investigations confirm the more rapid migration of strontium than cesium observed by many workers but also suggest limitations of the static method.

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2.5.6 Application of models to soil-food chain transfer

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Of the many models developed for predicting the atmospheric transport of a radioactive release, fallout patterns, etc. (e.g., see ref. 188), the "SPADE" model for soil-food chain transfer (79) is of particular interest here. In one exercise two fallout situations were considered: An initial "spike" fallout episode leading to a ground deposit of 30 MBq m⁻² or a "continuous uniform" deposition equivalent to total ground deposition at the continuous rate of 30 MBq m⁻² year⁻¹. The model further provided for separate crop-growing and -dormant (winter) phases, effects of harvest, ploughing, etc.

Following "spike" deposition over pasture the model indicated an initial rapid buildup of cesium-137 in milk within 10 days to a level of approx. 3.2 MBq l⁻¹ which declined to less than 0.5 MBq l⁻¹ after 100 days. Under conditions of "continuous" deposition the achievement of an effective steady level of 0.5 MBq l⁻¹ was indicated after about 1 year. Some comparative data for predicted levels of cesium-137 in various foodstuffs are illustrated in Table XVII from the same report (79, p. 151). As indicated earlier the model also shows relatively very much lower uptake of the actinides or transuranium isotopes.

TABLE XVI

Migration of radionuclides down the soil profile.

Comparative parameters for top 9-cm horizon of cambisole: pH - 4.4; organic carbon - 2.4 % (from data of ref. 72)

	Cesium-137		Strontium-85/90	
	Method:			
	Static	Fallout	Static	Fallout
Distribution coefficient - K (cm ³ g ⁻¹)	60	36	110	21
Retardation factor - R (as implied by Eq.7 on basis of d = 1.25 g cm ⁻³ & V = 0.2)	376	216	690	132

Migration rate cm day^{-1} for pore water velocity of $1 \text{ cm day}^{-1} - W$ (as implied by Eq . 6) For $W = 1 \text{ cm day}^{-1}$ effective rainfall would be cat 2 mm day^{-1} or 72 cm year^{-1})	2.7×10^{-3}	4.6×10^{-3}	1.5×10^{-3}	7.5×10^{-3}
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TABLE XVII

Cesium-137 contamination levels (CL-fresh weight basis) in foodstuffs indicated by SPADE model for different input scenarios (from ref. 79)

	MBq kg^{-1}		
	Year ⁻¹	Year ⁻²	Year ⁻³
"Spike deposit of 30 MBq m^{-2} "			
Leafy green vegetable (harvested after 200 days)	2.6	0.006	0.008
Cereals (harvested after 120 days)	4.8	0.4	0.2
Beef (270 days to slaughter)	0.26	0.17	0.14
Milk (after 270 days)	0.04	0.03	0.02
"Continuous" deposit at $30 \text{ MBq m}^{-2} \text{ yr}^{-1}$ (Times in days as for "spike")			
Leafy green vegetables	2.2	2.4	2.4
Cereals	0.95	1.6	1.9
Beef	2.8	2.9	3.1
Milk	0.42	0.44	0.47

It will be of interest to compare such predicted levels (as fractions of the "spike" deposit) with post-Chernobyl experience in Europe (146). As indicated elsewhere (125), considerable time may have to elapse before a full picture emerges of the behaviour of 'Chernobyl' fallout over soils.

2.6. Detection and measurement

2.6.1 Importance of early notification

2.6.2 Sampling and monitoring

2.6.1 Importance of early notification

The 'Chernobyl' experience certainly demonstrated the importance of early notification of unintended radioactive releases. Prompt notification and communication to the levels of national, agricultural extension service and local monitoring centres (e.g., those of agricultural or environmental research and teaching institutes with monitoring facilities) could, in future, contribute a great deal to improved preparedness and attenuation of some of the consequences of fallout over agriculture, forestry or inland fisheries. Moreover, as indicated earlier, the timely dissemination of information coupled with an improved use of local weather forecasting could better provide for some anticipatory countermeasures (shelter of grazing livestock).

Timely information at the right level would also provide for the rapid mobilization of monitoring facilities and for the earliest detection of fallout over crops and soil.

2.6.2 Sampling and monitoring

Sufficient here to note that in addition to routine monitoring, e.g., for national atomic energy programmes (189; 190) there is a need for improved local soil and crop monitoring facilities worldwide (where necessary these could be based as a mobile unit on some suitable national centre) - especially for dry and/or wet deposition. Those would be the best and quickest indicators of likely soil, crop, and livestock exposure levels (see also Section 1.4.4). Post-Chernobyl experience has shown the value of grass sampling and monitoring as a fallout indicator because of its ubiquitous distribution and relative accessibility in both urban and rural areas (163).

The importance of representative soil sampling, and the needs for both 'objective' (random) and 'subjective' (e.g., of suspected 'hot-spot' areas see Section 2.3.4) will be no different from those of conventional soil sampling and analysis (e.g., 191).

In consultation with other UN Agencies (FAO, UNSCEAR, WHO and WMO) IAEA has initiated a new programme on Fallout monitoring in Environment and Food. This has led to the elaboration of an up-to-date and concise report on laboratory organization, sampling, and radiochemical analysis (192). This authoritative report should be consulted as a first step for further information on sampling and radiochemical analysis for fallout levels in air, water, soil, crops, etc.

Summaries and technical descriptions of the basic principles of sampling and monitoring for radionuclides, which have not changed during the last decade or so, are available (e.g., see 59, p. 487; 190, pp. 115-185).

2.7. Countermeasures, reclamation and use of contaminated soils

2.7.1 General considerations

2.7.2 The time factor

2.7.3 Ploughing, irrigation, leaching, harvest

2.7.4 Fertilizer and other amendments

2.7.5 Choice of crops; safety checks

2.7.6 Possible problems from non-reactor accidents

2.7.1 General considerations

As indicated earlier (section 1.2.1), a significant radioactive fallout episode represents an immediate challenge to radio-ecotoxicological knowledge and its application to the implementation of any necessary countermeasures. The global scale of radioactive fallout from the atmospheric testing of nuclear weapons in the '50s and '60s prompted much of the now classical work on the problems of soil-crop contamination (e.g., by Scott-Russell and his colleagues - see ref. 59, pp. 3-12, 79-88 & 657-662; ref. 53).

An important difference between fallout from the atmospheric testing of nuclear weapons and that from a serious nuclear reactor release such as that from Chernobyl can now be recognized. The earlier tests injected radioactive debris high into the stratosphere resulting in widespread and persisting fallout (180). A mean stratospheric residence time of the order of one year has been indicated (59, p. 5). The deposition of finely divided radioactive material has continued at detectable levels for many years (see Section 2.3.3). This, in turn, resulted in direct crop contamination by interception so that even later contamination levels of crops were due more to interception than by uptake from the soil (59, p. 6).

The "explosive" emission of radioactive debris from the Chernobyl reactor, on the other hand, reached a height of approx. 1 km before "horizontal transport began" (46, p. 84). Therefore, most of this radioactive material would be expected to remain in the troposphere and deposition to be associated with precipitation - as indeed was observed. This also implies that contamination of post-fallout sown crops will be largely the result of soil uptake or soil surface contamination.

At worst, topsoil (and floral cover) was so heavily contaminated by longer-lived radionuclides that reclamation for agricultural use would be neither economic nor acceptable in the context of local community or public health. This situation evidently occurred near the Chernobyl site and prompted the physical removal of topsoil from some areas within the critical 30-km zone for disposal at special sites (46, pp. 82-83). However, such high levels were relatively localized.

While it is difficult to assign quantitative parameters to the initial fallout pattern some indication can be made on the basis of available data. An assumed initial angular plume of 10° (194; 188) extending to 60 km from Chernobyl (46) would correspond to a segment fallout area of approx. $3 \times 10^8 \text{ m}^2$. If 2 % of the reactor's total radioactive content i.e., one half of the total emission (46, p. 81) had been deposited

uniformly over this area it would result in a deposition of some 5×10^8 Bq m⁻² of significant radionuclides (iodine, cesium, strontium, ruthenium, plutonium). However, if the remaining half of the total emission were uniformly deposited over the total affected area of Europe of some 10^{13} m² this would correspond to an average deposit of the order of 10^4 Bq m⁻². In fact, of course, the deposition was very far from uniform (see Section 2.3.4) but, evidently, there were no levels so high as to indicate the need to evacuate local populations or to remove topsoils. Levels deposited in fact were, of course, also reduced by the radioactive decay of shorter-lived radionuclides such as iodine-131 during atmospheric transport and after deposition. Moreover, the fraction deposited over mainland Europe outside the U.S.S.R. must have been considerably less than one half because of its widespread detection beyond Europe. A fraction of one quarter has been suggested (104).

Given levels which do not indicate drastic intervention such as physical removal of topsoil or the temporary evacuation of local communities; then what are the prospects for continuing, normal use, limited or modified use, or for the application of effective countermeasures ? These questions are briefly addressed on the basis of existing information in the sections below (see also section 1.2.4 and ref. 53, pp. 509-518).

It is important to recall that, in principle, no remedial measure should be undertaken at farm, extension or advisory service level without the guidance of the appropriate radiological protection or public health authority (2, p. 15). There could, conceivably and otherwise, be a possible hazard to the personnel involved or, indeed, be implementation of a completely unnecessary or unsuitable countermeasure. The IAEA has provided machinery for assistance and guidance on the problems of 'off-site response to a nuclear accident (98; 193).

Finally, monitoring may indicate sufficiently low levels that, on the basis of national or recognized intervention levels for harvested products, and on the basis of crop uptake to be expected in future crops, no action of any kind is needed and agricultural use can continue unchanged.

2.7.2 The time factor

The timely harvest of exposed crops, cut grass, etc. and their removal would, of course, eliminate that proportion of intercepted fallout (see Section 2.5.2 and 2.7.3). In the absence of further fallout episodes or any significant continuing, fallout, the potential for soil-crop transfer will diminish with time. Firstly, as a result of radioactive decay, especially of the shorter-lived radionuclides (e.g., iodine-131, ruthenium--103, strontium-89) and, secondly, as a result of movement down the soil profile by leaching,, mechanical disturbance (cultivation practice, movement of soil mesofauna, etc.) and by effective mobilization by microbiological action (76).

The decrease in soil--plant transfer has been quantitatively studied (e.g., 75, pp. 260-264). The decrease may not be sufficiently rapid to result in a corresponding removal of all possible constraints. For example, a later new seasonal growth of fresh pasture may lead to a second smaller yet significant transfer into the new grass and rise in the radionuclide intake by grazing livestock, as recently warned for some hill-

farming areas in North Wales for the post-Chernobyl spring of 1987 (195).

A later rise in dairy cattle, etc. could also result when livestock are moved to winter shelter and fed silage or hay which had intercepted fallout or undergone soil uptake before harvest and before any significant decline in soil levels (88, p. 14). For an illustration see Section 3.3.

The relative significance of soil surface deposit and crop-uptake by interception or from the soil through the crop roots as contributors to the absorbed radiation dose will also vary with time. For example, as contributors to the total dose received by farm personnel "living off the land".

This can be illustrated as follows: The "conservative" scenario (Section 2.5.3) for committed dose equivalent as a result of dietary intake for one post-accident year is indicated to be less than 400 μ Sv. The integrated dose from external radiation for a worker on the same diet who spent 8 hours each day for 6 days in each week on the unploughed or uncultivated land and, assuming conservatively, that the effective deposit remained on the surface at 10,000 Bq m⁻² of cesium-137 (i.e., neglecting radioactive decay, soil penetration, crop removal, etc.) will be (Eq. 1):- 52 (weeks) x 6 (days week⁻¹) x 8 (hours day⁻¹) x 0.01 (SD_M) x 0.95 (CF for cesium-137) = 24 μ Sv approx. (i.e., 6% of the dose equivalent committed through dietary intake).

Now consider the same worker in the first critical 10 weeks (Intermediate Phase) after the fallout episode. Intake from local inland lake fish will be lower than indicated in Table XVI, or even negligible, because of the time needed for movement of the radionuclide in the aquatic food chain and its bioconcentration in fish (Kornberg & Davis in ref. 53, pp. 383-418). However, if the same farm worker consumed his local freshly exposed vegetables and cow's milk (of cattle grazing on freshly exposed pasture), contamination levels (CL) by interception of the order of at least 1,000 Bq kg⁻¹ fresh weight of green vegetables might be expected. Assuming an intake of 10 kg fresh weight of green vegetables in the 10-week period (i.e., until completion of the exposed harvest) with 150 kg of drinking water (assumed to be contaminated as initially at approx. 2 Bq kg⁻¹) and 40 kg of cow's milk, then a dose of the order 500 μ Sv would be committed. The external dose on the same basis would be approx. 5 μ Sv i.e., about 1% of the dietary-based commitment.

It follows that the external dose contribution may not decline so rapidly as that from the diet but, on the basis of a 50-yr. integrated projection for external dose (when soil penetration and radioactive decay will become significant), it will remain by far the lesser radiation dose contributor. However, it could become relatively more significant if dietary intake become based on products from an unexposed area, or effective soil-plant transfer factors declined more rapidly than soil surface radiation emission (196). The continuing accumulation of post-Chernobyl data will surely clarify this situation in due course (124).

2.7.3 Ploughing, irrigation, leaching, harvest

As indicated (see Section 2.5.1) ploughing will extend the vertical distribution of an initial deposit, reduce the level of above-surface radiation, and the potential of transport by erosion and run-off. However,

leaching tends to be very slow because of the cationic nature of the radionuclides, and because of the immensely low chemical concentrations likely to be involved, at least until isotopic dilution by any available naturally present element, or by cationic displacement by chemically related cations.

Effects of ploughing on soil-plant transfer are not large. Early work indicated a reduction of only 25 % by ploughing-in a surface deposit to 28 cm (58). Likewise, the uptake of actinides was relatively little affected by ploughing (77, Vol. I, p. 18) which, however, tends to be low in any event (see Section 2.5.2).

The effects of different tillage on the profile distribution of surface strontium-89/90 have been quantified (77, Vol. I, pp. 97-98). Almost all the added radionuclides remained in the top 15 cm of untilled soils while deep ploughing (to 30 cm) resulted in 30% moving into the 10 to 30-cm profile.

The use of "solvents" has been mentioned in connexion with the "fixation" of radionuclides in the highly contaminated soil around Chernobyl (46, p. 83). This suggests the admixture of ion exchange resin suspensions or irrigation water containing added cationic solutions of (e.g., of calcium, potassium and strontium salts) which would be expected either to "fix" the radionuclides or reduce the effective soil-plant transfer.

It has been recognized that the removal and safe disposal of foliar-intercepted fallout can greatly reduce the level of soil contamination (89; 193). An obvious limitation is that the presence of such an effective cover-crop will depend very much on location, growth status, and weather at the times of fallout. The most vulnerable time would, equally obviously, be that of the common bare fallow periods of modern agricultural practice.

Interception by woodland or 'closed forest' areas will also be important in the protection of underlying soils but, in this case, without harvest and removal. Intercepted fallout would be largely retained by the foliage or in ground surface litter as a result of post--fallout abscission (see Section 2.5.2). Near the Chernobyl site forest fire prevention was recognized as an important factor in the role of the forest as "long term accumulators of radioactive substances" (46, p.82).

Should eventual clearance of woodland or forest for crop cultivation or pasture be undertaken, removal and suitable disposal of the litter mat might be indicated as desirable by predisposal monitoring.

The effects of irrigation, whether part of normal practice or as a deliberate measure to accelerate movement of the radioactive deposit from crop and soil surface into the soil profile, will clearly depend upon the quality of the irrigation water. Other things being equal, it will especially depend on pH, cationic species, and their concentrations in the irrigation water for the reasons briefly indicated earlier. In practice many other factors would have to be considered such as standing crop needs, soil structure, water table, evapotranspiration, etc. as reviewed elsewhere in relation to "leaching fractions" (198). In any event the downward migration of radionuclides tends to be relatively slow in relation to water infiltration.

2.7.4 Fertilizer and other amendments

Increased availability of isotopic or some chemically-related elements can reduce the soil-plant transfer (98; 58). For this reason the uptake of strontium-89/90 tends to lessen with liming and increased pH (77, Vol. I, p. 107) and that of cesium-134/137 by the addition of K-P fertilizer (77, Vol. I, p. 331; 91).

In this connexion the benefit versus cost would need careful consideration unless the amendments were consistent with normal practice. For example, soil amendments with natural cesium salts would probably be far more expensive and less effective than, say, the use of a crop from the untreated soil as animal feed but amending this feed with the commercially available (e.g., see ref. 197) cesium iodide. However, while that would be expected to reduce the appearance of cesium-134/137 and iodine-131 in meat it could increase the fraction of total iodine-131 appearing in the milk of lactating cattle (see Section 1.2.4). The use of iodine compounds to reduce possible transfer of iodine-131 through milk into the human thyroid is well recognized as an emergency prophylactic (199, pp. 174-178) and so applied with success around Chernobyl (46; 124).

2.7.5 Choice of crops; safety checks

Choice of crop would only be a post-fallout option. The low frequency of accidental releases of any significance to agricultural soils suggests that modified practices purely on account of proximity to some nuclear installation would not be justified unless choice had no economic implications anyway. In that event, vegetables, for example, would be wiser (high probability of interception and economic removal and disposal) than viticulture or cash crops for export (because of the potential for international constraints whether technically justified or not). However, the high interception potential of conifer stands (see Section 2.5.2), their relative insignificance to the human food chain and absence of human habitation suggest their suitability as the immediate reactor site environment. This possibility was not, apparently, considered in earlier discussions of reactor siting (see Section 1.1.3).

Changed cropping practice might be indicted under some circumstances including the time factor. While only surface contamination obtained, "minimum tillage followed by the planting of a deep-rooted crop should reduce the uptake" of radionuclides, compared with that of shallow-rooted crops (199, p. 273).

Safety checks. At some point after the imposition of possible emergency constraints i.e., at a stage in the Recovery Phase (see Section 2.4.1), it might be desirable to check the soil-plant transfer potential of the earlier exposed soils before re-sowing or committing a new programme of cultivation. For this purpose a radiobio-assay using a fast growing plant under temporary glass or plastic cover (to accelerate growth but using the undisturbed soil) would be useful. A plant species with a high TF value for the residual soil radionuclides should be chosen. Such values for a wide range of plant species have been documented (e.g., 77; 178).

2.7.6 Possible problems from non-reactor accidents

This review has been concerned with the problems of soil contamination by fallout as a result of an unintended nuclear reactor release into the atmosphere. However, other kinds of accidents are possible as

a result of some failure in the nuclear fuel cycle or in some other application of nuclear science. For example, a release of cobalt-60 as a result of fire or explosion at a gamma-irradiation facility.

Other kinds of accident have, indeed, occurred. According to reports, a military aircraft carrying "thermonuclear weapons" crashed and exploded on the ground near the Spanish village of Palorames in January 1966 resulting in the release of plutonium (200). The destruction of local tomato crops was ordered and some 500 truckloads of soil were removed. Despite the obviously serious nature of this accident the effects evidently remained localized.

It seems highly probable that the effects of a nuclear accident other than a major reactor release would also be relatively localized and be effectively contained by the national radiological and public health authorities concerned. However, global fallout of plutonium-238 has been recorded as a result of at least one 'burn-up' episode in the upper atmosphere of a space-programme satellite containing a plutonium generator. This occurred in the Southern hemisphere in April, 1964 (201); but the resulting levels of plutonium-238 found in soils have been some two orders lower than those of plutonium-239 + 240 as a result of nuclear weapons testing in the atmosphere (145).

A large number of studies have been, and are being, made on the behaviour and significance of routine radioactive releases into the agriculture (and fisheries) environment (e.g., 62; 74; 75; 77; 170; 202; 214; 215). The evidence suggests that these releases are effectively controlled and represent no significant threat to agricultural soils or to the health and welfare of the dependent communities.

2.8. Concluding comments; some questions and needs

Notwithstanding its tragic human consequences at the local community level, the Chernobyl accident in April, 1986 has provided some new opportunities. Firstly, for obtaining answers to many important and relatively neglected practical questions on the basis of the newly emerging data. Secondly, to provide for much better preparedness for the impact of future accidents upon agriculture and upon the dependent communities.

There will, surely, be accidents in future. The problem now appears to be that of improved protection of exposed agricultural (forestry and fisheries) resources and the welfare of their dependent communities. This aspect of nuclear accident emergencies seems to have been relatively neglected. Moreover, unlike other technology-based accidents, a major release of radioactive material into the atmosphere can have wide-ranging consequences as a result of fallout over agricultural soils. However, these consequences could be largely contained or attenuated, given the necessary international cooperation and prompt communication.

Despite the massive range of reports and publications on the behaviour and effects of radionuclides in the soil-plant system, it remains difficult to identify useful translation into practical and simple language for guidance and clarification at agricultural advisory service or farmer level. This could result in serious post-accident problems in future; especially in countries which may lack a nuclear science or monitoring infra-

structure but which might, nevertheless, be significantly exposed to fallout from an out-of-state release. For these same reasons 'Chernobyl' prompted a great deal of unnecessary fear and suspicion at farm community level, even within industrialised countries with their own nuclear power programmes.

Against this background, some unanswered questions and related needs have been identified (see also Sections 1.4 and 1.5).

- Once deposited, radionuclides tend to move relatively slowly down the soil profile and may sustain crop uptake for many seasons after the initial deposit. Fortunately, soil-plant transfer, while variable is usually very fractional, especially for the more radiotoxic actinides (see Section 2.5.2). Soil-plant transfer tends to decline slowly with time for various reasons. There is a need to quantify the benefit-cost ratio of countermeasures involving ploughing, chemical or special irrigation amendments over and above those of normal agricultural practice - all, of course, as a function of the initial level of deposit. Would it be more effective to accept crops from untreated soils as livestock feed but amend this feed with suitable chemicals to reduce animal absorption of the radionuclides (see Section 2.7.4)? Alternatively, what might the prospects be for diverting the contaminated crop to alternative use? E.g., wheat for fuel alcohol production and animal feed as already developed for wheat surpluses in Sweden (203). Would such diversion lead to any significant occupational radiation hazard?
- Existing standing crops, grass, etc. clearly represent a potentially important fallout-intercepting and consequent soil-protective cover. Emerging post-Chernobyl data should be specifically studied in that context to quantify its potential value as a protective measure in future (see Sections 2.5.2 and 2.7.3) and for the development of internationally-available guidelines.
- There is a need to study the most effective ways of harvesting post-fallout crops, which have successfully intercepted fallout, in order to determine practicable methods of disposal. For example, by composting or burning and returning the compost or ash later to the soil or retaining the compost or ash at a protected site? Would the radionuclides of returned ash or aged compost be as available for future soil-crop transfer as radionuclides directly deposited on the unprotected soil? Radionuclides in the ash might have undergone more effective isotopic or chemical dilution. In any event the treatment of ash would be far more economic than treatment of the original soil areas.
- Precipitation and weather evidently played a critical role in post-Chernobyl fallout (see Section 2.3.4). This indicates the need for a feasibility study for advance warning at farmer level of possible or probable fallout episodes. Such warning could be of practical value. For example, with warning a farmer might usefully, and even critically, delay the harvest of, say, mature vegetable crops and effectively protect otherwise fully-exposed soils (see Sections 2.7.2 and 2.7.3).
- There is, evidently, scope for the development of improved freshly harvested food crop decontamination procedures by simple washing or soaking in suitable 'carrier' salt solutions (see Sections 1.2.4 and 2.4.2).

The U.N. Agencies (especially IAEA, FAO, UNSCEAR, WHO, WHO) and other relevant international

organizations (especially CEC, OECD-NEA, ICRP, IUR) have an important opportunity for cooperation and for the elimination of some of the duplication and confusion in this subject area - even at the scientific level. An opportunity for the joint preparation and publication of simple explanations and guidelines on anticipatory- and counter-measures for agriculture and fisheries in the event of a future serious accidental release of radioactive material into the environment. Likewise international agreement on the principles of insurance and compensation, and appropriate derived intervention levels for soils, crops, and for products moving in international trade.

Finally, it is important to recognize that fallout radionuclides are only part of the range of chemical contaminants of agricultural and forestry soils worldwide as a result of agrochemical usage, irrigation, industrial, and transport emissions from remote sources (e.g., as acid rain). This underlines the importance of considering any particular soil contaminant in a comparative and integrated context (209).

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3. Appendix notes on intervention and derived intervention levels in relation to food and agriculture

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[3.1 Intervention levels](#)

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[3.3. Derived intervention levels as a function of time and food processing](#)

3.1 Intervention levels

In the event of a nuclear accident the limitation of human exposure to radiation may only be achievable by "intervention" (44). Moreover, as demonstrated by Chernobyl this will probably involve constraints on, or changes in, agriculture, forestry and fisheries practices and upon livestock movement, product harvest, distribution, processing, and trade with implications for the dependent communities.

A post-accident intervention level of dose commitment for the public has to be translated into the corresponding and measurable levels of ground deposit (Bq m^{-2}) of the significant radionuclides present, and into the related levels in food and drink as consumed (Bq Kg^{-1} or Bq l^{-1}). This then provides for the application of derived intervention levels (DIL's) in the same units. These are the relatively easily monitored levels in food or environment, below which intervention would not be justified under the circumstances or, above which intervention would be indicated on the grounds of public health.

ICRP has tabulated radiation dose commitment conversion factors in terms of Sv Bq^{-1} , in consumed food and drink (204) in connexion with occupational exposure. The same approach is used and extended in the development of guidelines for intervention levels in post-accident situations by IAEA (81). A few dose per unit intake factors are illustrated in Table I below. The relatively higher H_{eff} for the 'critical' group of infants should be noted. While not within the scope of this review, ICRP (54; 205) has quantified the non-stochastic and stochastic relationships between health effects and radiation dose.

TABLE I

Conversion factors for committed effective dose equivalent per unit radionuclide intake (from ref. 81, p. 55) - $\text{nSv.Bq}^{-1} = 10^{-9}\text{Sv/Bq}^{-1}$

Radionuclide	1 - yr infant	10 - yr child	Adult
Strontium-90	120	46	33
Ruthenium-106	40	13	6

Iodine-131 (thyroid based)	3700	1200	440
Cesium-137	13	12	12
Plutonium-239	49	21	14

The same IAEA publication (81) includes guidelines on terminology, and on the relationships between intervention levels of radiation dose (ILs), and derived intervention levels (DIL's). In its general form a derived intervention level was defined (81, pp. 18 et seq):

$$\text{DIL} = \text{IL}/\text{DCF}$$

where IL is the intervention level of radiation dose commitment for the exposed person and DCF is the dose conversion factor, both for the particular situation, e.g., radiation exposure from the ingestion of contaminated food; or for external radiation exposure from a ground deposit (see ref. 81, pp. 2325).

While a consensus has emerged on the guidelines for establishing "lower-tier" and "upper-tier" ILs and DILs (e.g., see refs. 44; 205; 100; 81) those actually adopted will depend on the local or national situation after the accident or emergency as explained below (Section 3.2).

FAO, meanwhile, adopted a lower IL of total body dose commitment of 5 mSv for the first post-accident year for the purpose of lower-tier DILs for food moving in international trade (181; see Section 3.2), and a dose commitment of 1 mSv for subsequent post-accident years. Taking into account the "weighting factors" (54), first and subsequent post-accident-year dose commitments of 50 mSv and 10 mSv were respectively adopted for radionuclides affecting specific organs.

Chernobyl has also demonstrated the need for improved international agreement, not only on terminology and guidelines, but also on specified post-accident IL's (206) as a basis for DILs for food and feed moving internationally. FAO's initiative in this context was timely. If wide agreement could not be achieved, e.g., in relatively nuclear-power free areas such as Australia (207), then as wide agreement as possible might usefully be sought, e.g., in food trading zones which include significant nuclear power programmes and countries highly dependent on food imports such as Japan (208).

3.2 Derived intervention levels for food moving internationally

A major problem after "Chernobyl" were the disparate "action levels" adopted by different countries for the acceptability of food for import or domestic consumption. For example, for cesium-137 in milk such levels ranged from 50 to 4,600 Bq l⁻¹ (181).

Such disparities may have arisen, understandably, as a result of differing interpretations of two existing

international guidelines: The "ALARA" principle (see ref. 121; Section IV), and "The establishment of..... intervention levels for particular circumstances is the responsibility of the competent national authorities" (34; 54; 44; 205).

Unfortunately, the detrimental consequences in terms of constraints on food harvest, movement (including that of livestock feed), international trade, and upon the welfare of the dependent communities had been underestimated or unforeseen.

FAO took a timely step towards a solution to this problem. This involved the elaboration and recommendation for future international recognition of "Interim International Radionuclide Action Levels for Food" (i.e., for food moving in international trade). The acronym "IRALFs" for these levels was proposed (181).

IRALF's were designed to provide for wide margins of post-accident radiological health safety for importing communities, for minimizing constraints in future, and for improved protection of the welfare of agriculture and fisheries communities against anomalous trade barriers. The levels can be applied to single radionuclides or mixtures (181, p. 11) and would lend themselves to simple monitoring, certification, and application. The levels represent those below which export or import restrictions would not be technically justified, taking into account "economic and social considerations" in the international context.

As implied by their definition, IRALF values provided for periodical international review after some accidental release, a provision already adopted for EC countries (85).

3.3. Derived intervention levels as a function of time and food processing

IAEA has addressed the problems of derived intervention levels (DIL's) for radionuclides in foods (81). The basis is comparable with that adopted for 'IRALF' levels (above) by FAO but refined to take into account changes with time in the radionuclide concentration in the foodstuff (and, therefore, the time of DIL application) during the year of intake. Thus, "on the assumption that only one nuclide and one foodstuff contributes to the diet", the DIL, in its simpler form, was defined as follows:

$$\text{DIL} = \text{EDL}/I \cdot \text{DCF} \cdot G \quad \text{Eq. 1}$$

where: DIL (Bq kg^{-1}) is the intervention level to be applied at time t , EDL (Sv) represents the effective intervention level of dose and will represent that fraction of the total committed radiation dose equivalent allowed for the intake of food in the one year, e.g., allowing for possible additional sources of radiation exposure. I (kg yr^{-1}) is the rate of intake of foodstuff as consumed. DCF (Sv Bq^{-1}) is the appropriate radiation dose conversion factor for that radionuclide. G (yr) is the ratio of "the integral over the one year of the nuclide concentration in that foodstuff" (Bq-yr kg^{-1}) to the concentration at time t (Bq kg^{-1}).

Any realistic advantage in this refined approach will depend upon some foreknowledge or model of the radionuclide in the foodstuff as a function of "real" time. However, given that condition and the same

basic assumptions above, the approach can be illustrated as follows:

Let the intervention level of dose for food restriction (EDL) selected by the appropriate authority for the post-accident year under consideration be L (Sv). Suppose the radionuclide concentration C (Bq kg⁻¹) is some function of time t (yr) such that $C = f(t)$ during the year under consideration (i.e., $0 < t < 1$). Further, suppose that the $C - t$ curve during the year is of the developing (i.e., as observed in "real" time) or predicted form illustrated in Fig. 1 below:

Fig. 1. Hypothetical concentration - time curve for radionuclide in foodstuff over one year period.

Such a curve might, for example, represent cesium-137 in the dried milk powder from dairy herds initially grazing on pasture following a "spike" deposition followed by a rise on transfer of the herd to winter shelter and feed which had been harvested at an earlier post-fallout state. The initial decline will be due to the short "effective" halflife of cesium in the cow following an initially high intake of recent deposit while the later rise and near-horizontal part of the curve will reflect the 'steady-state' situation as a result of the more constant feed-radionuclide intake when the decline in the feed will be the result of radioactive decay alone with a halflife of 30 yr.

It follows that the equivalent dose committed during the year will be $W.DCF.C_m$ where W will be the total weight of foodstuff (kg) effectively taken in by the average exposed member of the population. C_m will be the time-weighted mean concentration of radionuclide (Bq kg⁻¹) in the foodstuff as consumed during the same year, i.e., A/t where A is the shaded area enclosed by the $C - t$ curve of Fig. 1 or, formally,

$$C_m = 1/t \times \int f(t).dt \text{ where } t = 1 \text{ (yr).}$$

Now suppose that DIL_t is the DIL for application at time t' ,

$$\text{i.e., when } W.DCF.C_m = L. \text{ Let } DIL_t' = C_m/G'$$

Then, by definition (above), $DIL_t = L/W.DCF.G'$ which represents a specific illustration of equation 1 ($W = I/t$ where $t = 1$).

Likewise $DIL_t' = L/W.DCF.G''$ for the DIL applied at time t'' for the same limiting value of EDL. Note that in the illustration of Fig. 1, G will exceed unity for DIL_t' but will be less than unity for DIL_t

It may also be noted that the ratio G will be unaffected by the actual value of C_m because, for a particular model, "the relationship between the derived quantity and the primary intervention level of dose is linear" (ref. 81, p. 4).

In developing "interim" DIL's for food moving in international trade (i.e., IRALFs) FAO (181) has ignored changes in C during a year of export or import since the IRALF would be applied at the particular time of export and import and the foodstuff would be subject to certified monitoring. Moreover, once imported, changes as a result of significantly short halflives are taken into account. This approach has the advantages of simplicity and conservative caution since under these conditions C can only decline with t after the importation. However, equation 1 might be useful at exporter level as an indicator as to when an agricultural product would become internationally acceptable for export.

Equation 1 (above) can be modified to take into account the effects of applying the DIL at different stages of food processing from the point of harvest or collection (e.g., milk) as follows (81, p. 31):

$$\text{DIL} = \text{EDL} \cdot F / I \cdot \text{DCF} \cdot G \quad \text{Eq. 2}$$

The new modifying factor F is the ratio of radionuclide concentration in the food or drink at the point of DIL application (and implied sampling) to that level in the food or drink as ready for consumption. Thus,

F will exceed or equal unity. For example, if the DIL were applied as the "IRALF" to imported milk powder which would only be consumed as reconstituted milk (with uncontaminated water) then F would have a value of approx. 6.5 because milk contains approx. 15 % dry weight of solids (Dr. J.G. Davis personal communication). Likewise, the values of F would be of the orders of the reciprocals of the fractions illustrated in Table IV of Section 1.2.4 which quantify the effects of processing on fruit and vegetables, e.g., if the DIL were to be applied to "internal" leaves of freshly-harvested green vegetables or flesh of fruits, before processing, and for the consumption of the processed food.

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4. Glossary of terms, definitions, units, abbreviations, acronyms

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(see also Ref. 211)

becquerel (Bq) New unit of radioactivity = 1 radioactive disintegration per second (= 27 pCi).

CGS Classical centimetre-gram-second system of expressing physical dimensions.

Curie (Ci) Classical unit of radioactivity and that associated with 1 gram of radium. $1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$. (This unit is now superseded by the Bq).

electron volt (ev) Unit of energy in the context of ionizing radiation. 1 ev is the kinetic energy acquired by a free electron over an electrostatic potential gradient of 1 volt. $1 \text{ ev} = 1.6 \times 10^{-12} \text{ ergs}$. $1 \text{ Mev} = 1.6 \times 10^{-6} \text{ ergs}$.

erg CGS unit of energy and is the work done when a force of 1 dyne acts through a distance of 1 cm. $1 \text{ erg} = 10^{-7} \text{ J}$.

gray (Gy) New unit of physically-absorbed radiation dose $1 \text{ Gy} = 1 \text{ J kg}^{-1} = 100 \text{ rad}$.

joule (J) SI unit of energy and is the work done when a force of 1 newton acts through a distance of 1 meter. $1 \text{ J} = 10^7 \text{ ergs}$.

rad Classical unit of physically absorbed radiation dose. $1 \text{ rad} = 100 \text{ ergs g}^{-1} = 10^{-2} \text{ J kg}^{-1}$.

rem Classical unit of "absorbed dose equivalent" (H) in the context of radiological health protection which takes into account the different levels of biological damage for the same physically absorbed dose. Thus, $H = D \times Q$ where Q is the "quality factor" for the type of radiation absorbed. $Q = 1$ for normal beta and/or gamma emitters, 10 for neutrons, and 20 for alpha emitters.

roentgen (R) Classical unit of external radiation level. 1 R is equivalent to an energy dissipation of 83 ergs g⁻¹ Of air or 93 ergs g⁻¹ of water or tissue. This unit is now superseded by the Gy or Sv.

sievert (sv) New unit of absorbed dose-equivalent (1 Sv = 100 rems). Note: $\mu \text{ R hr}^{-1}$ (old unit still in use for external radiation levels) $\equiv 1 \mu \text{ Sv}$ per 168-hr week - approximately.

SI Système Internationale of the newer units which include the Gy, Sv, kg, J. etc. which are often expressed in multiples or sub-multiples with standard abbreviations as follows:

Kilo (k) = 10^3 milli (m) = 10^{-3}

Mega (M) = 10^6 micro (μ) = 10^{-6}

Giga (G) = 10^9 nano (n) = 10^{-9}

Tera (T) = 10^{12} pico (p) = 10^{-12}

The following abbreviations appear in the text:

cm centimetre

cm² square cm

cm⁻² per square cm

m² square metre

m⁻² per square metre

m⁻³ per cubic metre

km² square kilometre

kg⁻¹ per kg

h⁻¹ per hour, etc., etc.

Note on "radiation dose" terminology (based on refs. 54;205; 211)

"Dose equivalent" The absorbed radiation dose from an internal or external source taking into account the different biological effects ("quality factor") per unit of physically-absorbed radiation energy (Gy) according to the physical nature of the radiation (e.g., alpha, beta and/or gamma) - expressed in Sv.

"Committed effective dose equivalent" The effective dose equivalent that will be accumulated in an individual during the conventional 50-year period following an intake of radioactive material into the body. This takes into account its physiological distribution within the body, concentration in specific organs, tissues, effective half-life, etc. (see footnotes to Table I in Part 1) - expressed in Sv. This provides the basis for estimating possible "somatic" health effects (i.e., those manifest in the exposed individual) including "non-stochastic effects" (see below) such as skin- burn as a result of an acute exposure which may be dose-related, and for which a threshold dose level may exist (cf. "no-effect" level for pesticide residue).

"Collective effective dose equivalent commitment" The projected (i.e., dose rate-time integrated) total dose equivalent which will be accumulated over infinite time into the future by the exposed population - expressed in man-Sv. This parameter, on the basis of earlier and recently reviewed data (216) on radiation health-risk factors provides for estimating the risks of "hereditary" effects (i.e., those which may become manifest in the descendants of the exposed population). Also of "stochastic effects" which can only be quantified in terms of the probability of their later occurrence in the exposed population,

such as the incidence of radiation-induced cancer.

Organizations and acronyms

ALARA - Principle Basic principle that radiation doses should be kept As Low As is Readily Achievable, see ref. 121.

ANS American Nuclear Society

BEIR - Report Report on the Biological Effects of Ionizing Radiation (U.S.A.)

CEC Commission of the European Communities

CIPF Confédération International du Commerce des Pailles Fourrages tourbes et derives

COE - COA Council of Europe - Committee on Agriculture

DHHS Dept. of Health and Human Services (U.S.A.)

EC European Community

EPA Environmental Protection Agency (U.S.A.)

ESNA European Society of Nuclear Methods in Agriculture

EURATOM Effectively the IAEA of the EC and administered by the CEC

EULEP European Late Effects Project Group

FAO Food and Agriculture Organization of the UN

FAO - SCRE FAO - Standing Committee on Radiation Effects

FDA Food and Drug Administration (U.S.A.)

FDA - FSIS FDA - Food Safety and Inspection Service

GSF Gesellschaft für Strahlen- und Umweltforschung (F.R.G.)

IAEA International Atomic Energy Agency (UN)

IAEA - IAC IAEA - Inter-Agency Committee

ICRP International Commission on Radiological Protection

ICRU International Commission on Radiation Units and Measurement

ICSU - SCOPE International Council of Scientific Union - Scientific Committee on the Problems of the Environment

IIASA International Institute of Applied Systems Analysis

ILO International Labour Organization (UN)

INSAG International Nuclear Safety Advisory Group of IAEA (UN)

IUR International Union of Radioecologists

MHIDAS Major Hazard Incident Data Service (U.K.)

NCRP National Council on Radiation Protection and Measurements (U.S.A.)

NPT Non-Proliferation Treaty (UN)

NRCC National Research Council of Canada

NRPB National Radiological Protection Board (U.K.)

OECD - NEA Organization for Economic Cooperation and Development - Nuclear Energy Agency

SCUAE State Committee on the Utilization of Atomic Energy (U.S.S.R.)

SSI Statens Stralskydds Institute (Sweden)

UN United Nations

UNEP United Nations Environment Programme

UNSCEAR United Nations Scientific Committee on the Effects of Atomic Radiation

USAEC United States Atomic Energy Commission

USDA United States Department of Agriculture

WHO World Health Organization (UN)

WHO - RCE WHO - Regional Centre for Europe

WMO World Meteorological Organization (UN)

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